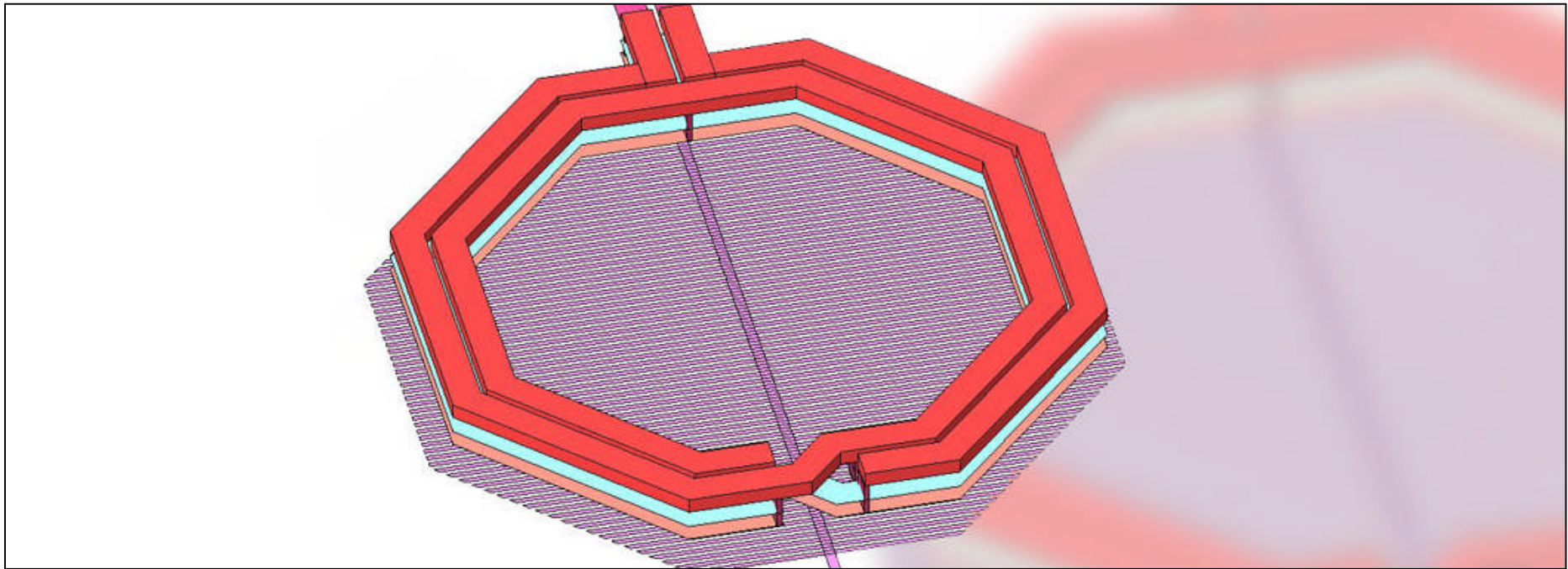


EM Analysis of RFIC Inductors and Transformers



Dr.-Ing. Volker Mühlhaus
Dr. Mühlhaus Consulting & Software GmbH, Witten

Do you love inductors?

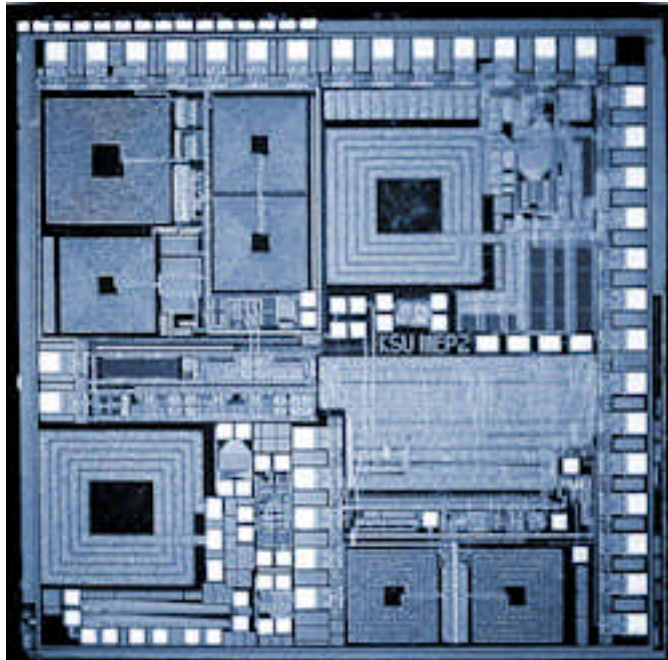


Image © Kansas State University

- Inductors from the design kit tend to have the wrong value, optimized for other frequency than we need
- Inductors are expensive devices: they are big, need a lot of expensive chip space.
- Then, why don't we try to design the best possible inductor for each new project?
- Customized inductors are difficult to design and optimize for your specific project

not

Why design customized inductors?

- Library inductors are like "one size fits all"
- With customized inductors, we get the performance that we need for this project:
 - Exact inductance as needed
 - Q_{max} and frequency of maximum Q as needed
 - Take advantage of multiple stacked metal layers
 - Design compact inductors where high Q is not needed, to save valuable chip space

How to design custom inductors?



- Specify the required inductance and Q factor and available space
- Use synthesis tool or layout generator
- Consult your company's EM guru to extract an EM accurate model
- Wait ... the guru is a busy man ...

- or -

- Use a workflow where you can EM analyze inductors yourself *without guru knowledge*

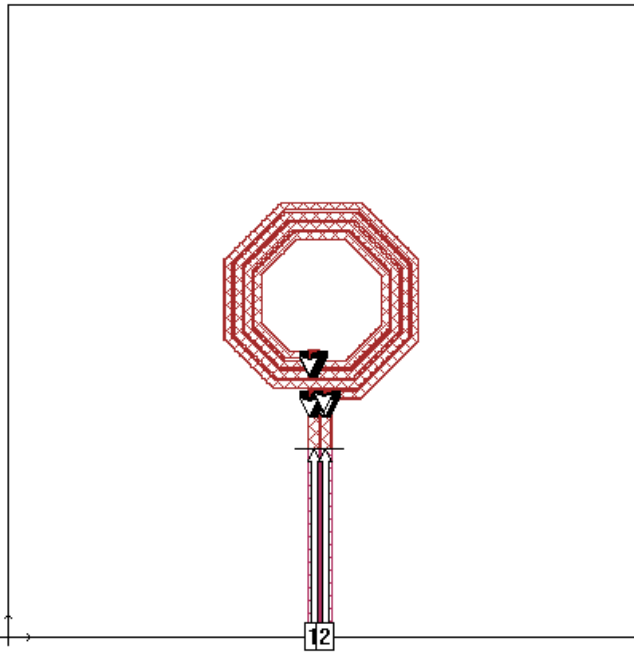
EM without guru knowledge?



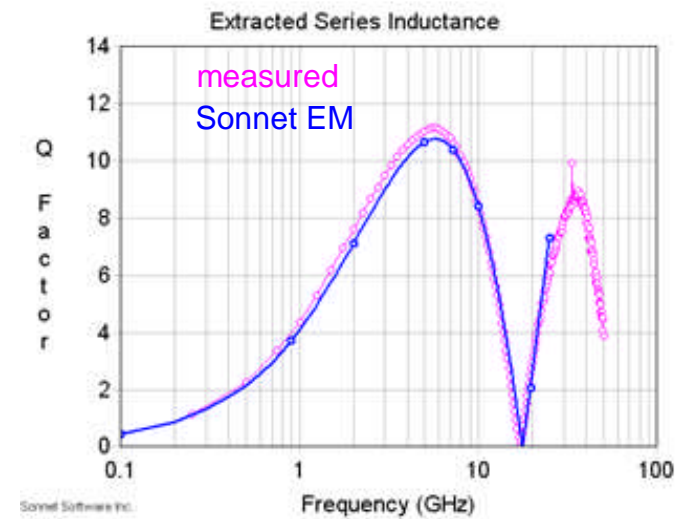
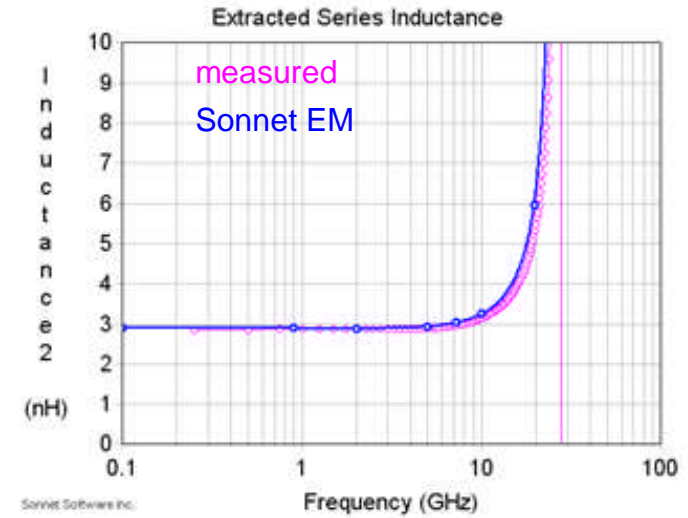
Well proven, accurate and easy to use:

- Use Sonnet planar 3D EM tool with Cadence Virtuoso plug-in integration
- Layer mapping and material files supplied by EDA support group
- Define model from within Virtuoso, using pre-defined simulation states
- Run EM simulation
- Sonnet creates broad band model and Cadence schematic symbol for results

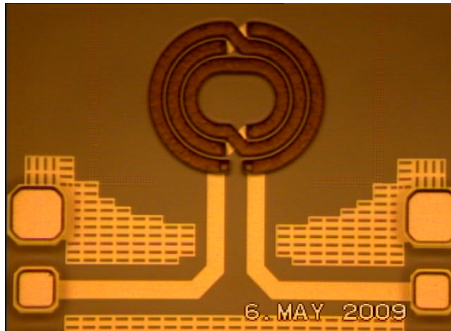
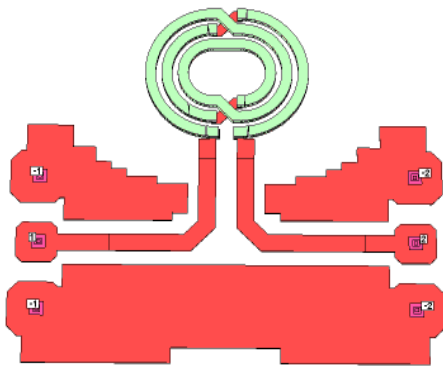
"Silicon Accurate" Results



Courtesy of IHP GmbH

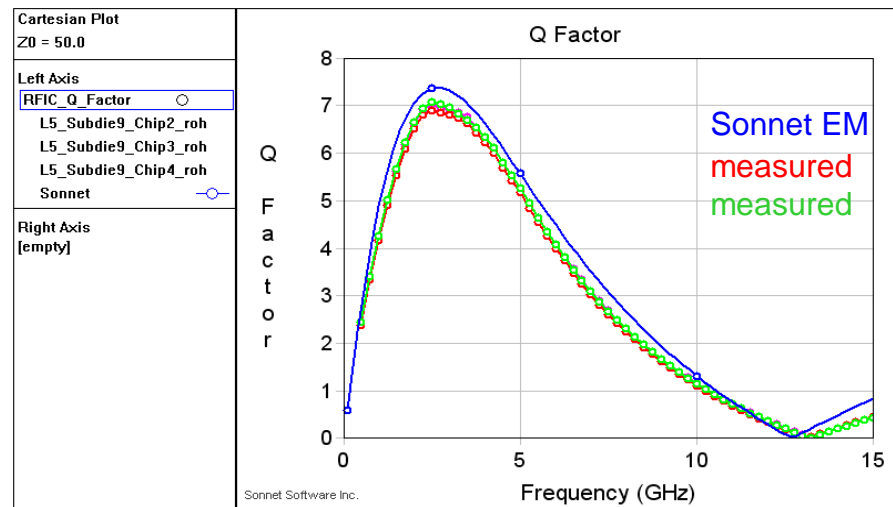
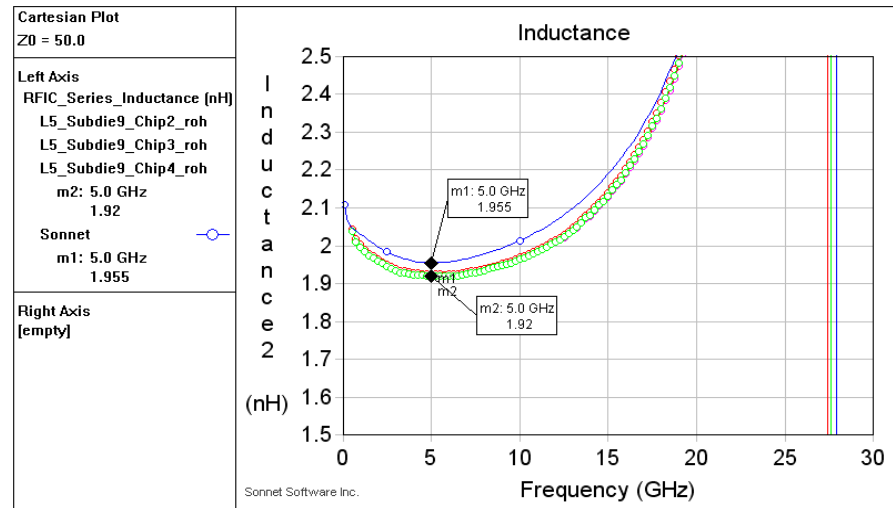


"Silicon Accurate" Results

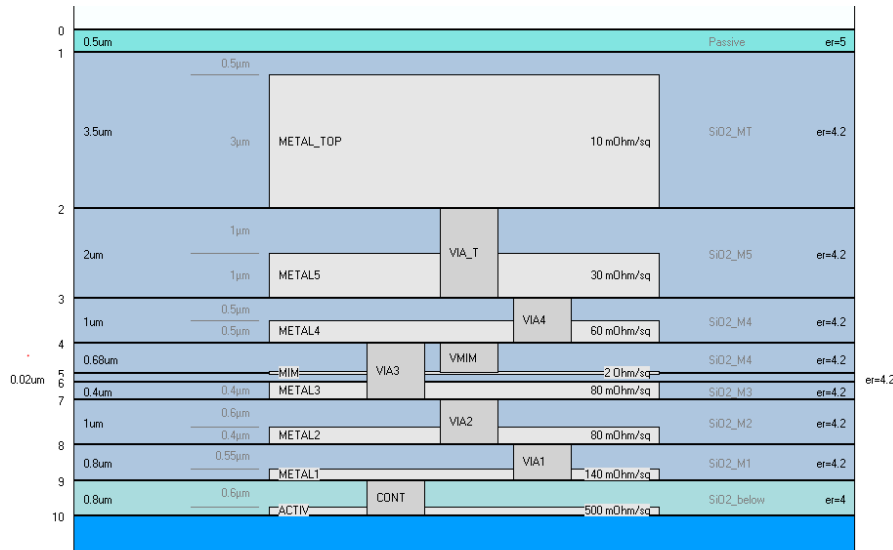


Courtesy of
Landshut Silicon Foundry GmbH
Analog Alchemy GmbH

Dr. Mühlhaus Consulting & Software GmbH



Technology File

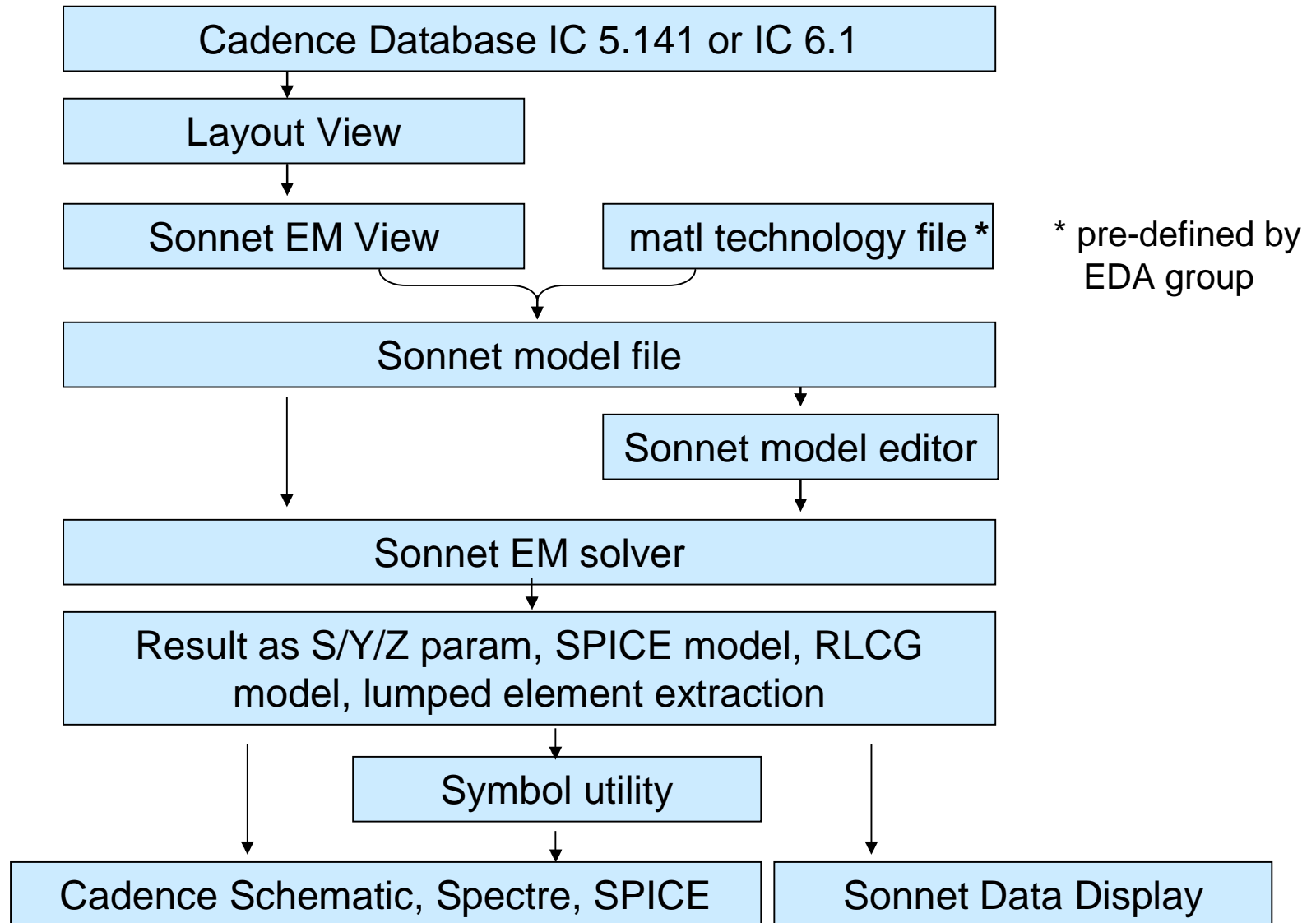


	Thickness [µm]	Material name	eps_r	S/m	Ohm*cm	µr	tand	tanm
- 0 -	1000	Air						
- 1 -	0.5	Passive						
- 2 -	3.5	SiO2_MT						
- 3 -	2	SiO2_M5						
- 4 -	1	SiO2_M4						
- 5 -	0.68	SiO2_M4						
- 6 -	0.02	SiO2_M3						
- 7 -	0.4	SiO2_M3						
- 8 -	1	SiO2_M2						
- 9 -	0.8	SiO2_M1						
- 10 -	0.8	SiO2_below						
- 11 -	300	Substrate						

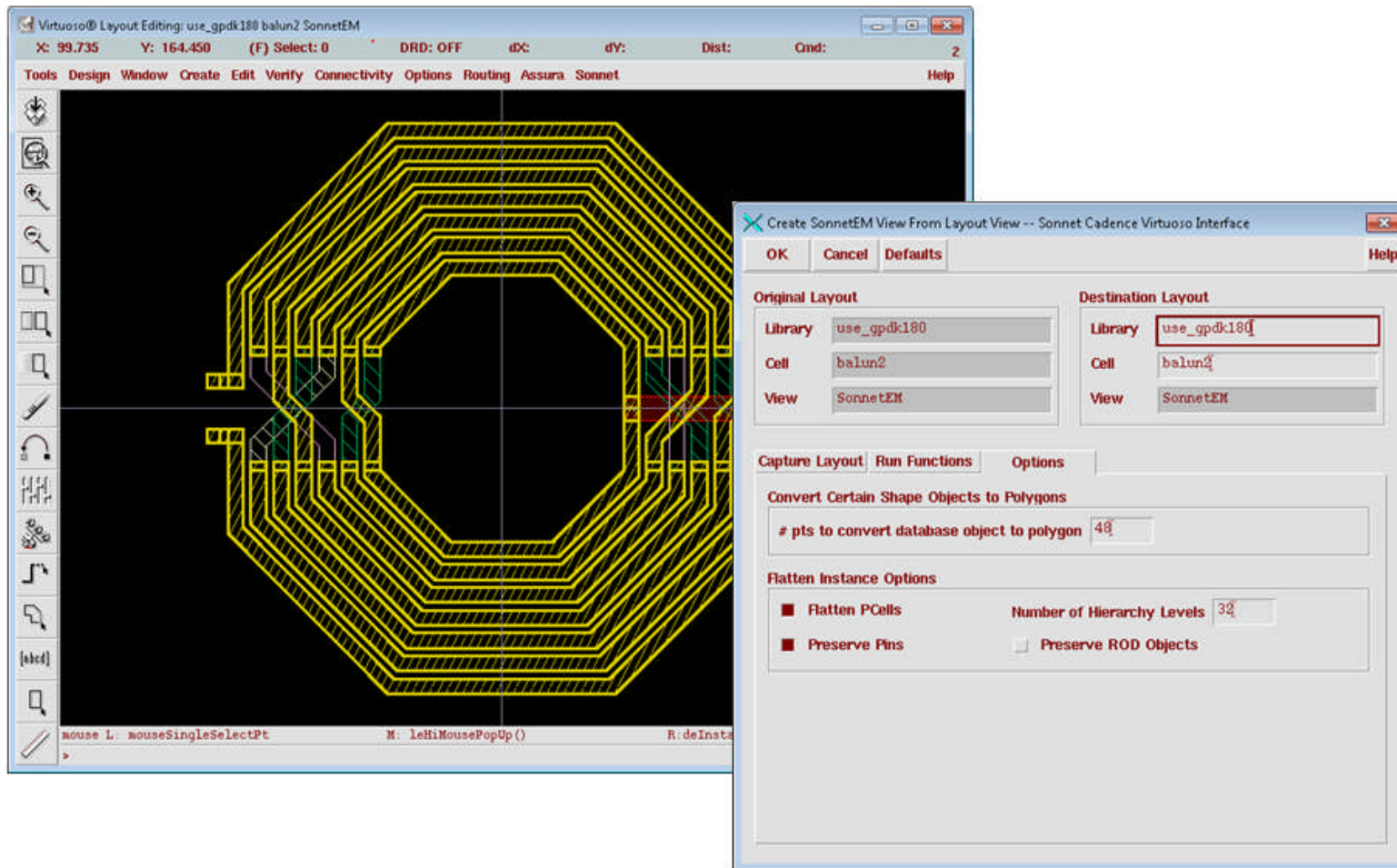
Dielectric Properties	
Material name	Substrate
Thickness	300 µm
epsilon r	11.9
loss tangent	0
<input checked="" type="radio"/> Conductivity	5 S/m
<input type="radio"/> Resistivity	20 Ohm*cm

- For simulation, the EM solver needs to know the layers and material data ("technology file")
- For some foundries, we supply pre-defined Sonnet technology files.
- Sonnet can import the technology data from an existing Assura profile
- Sonnet can import the technology data from an existing Agilent Momentum substrate file
- Various tools and translators are available to support EDA administrator's work with Sonnet technology files

Sonnet EM Analysis



Cadence Interface



Cadence Interface

The screenshot displays the Sonnet Cadence Virtuoso Interface. The main window shows the 'Design' tab with the following settings:

- Library: use_gpdk180
- Cell: balun2
- View: SonnetEM
- Length Units: micron

The 'Sonnet Frequencies' section contains a table with the following data:

#	Type	Range
1	Single	1 GHz
2	Single	5 GHz
3	Single	8 GHz
4	ABS	0.01 GHz to 80 GHz
5	DCPoint	0 GHz Automatic 1798.754748 KHz

Below the table, a status message reads: **> Sonnet properties from cell view were loaded successfully**

An open log window titled 'icfb - Log: /disk/usr/mkobasa/CDS.log' displays the following text:

```

done!
Loaded gpdk180/libInit.il successfully!
Loading layers.cxt
Loading alvs.cxt
Load shared object file /disk/app/cadence/virtuoso/assura4icdb/tools/lnx86/assura/lib/libavview.so
Version: 6(4)30DS: libavview.so version av4:1:Production:dfII5.1.41:5.10.41.500.6.130.09/25/09.08:53 (Logart05) $
Version: Assura.5.1.41, layout editor:5.1.0
rcxui.cxt was successfully loaded
Loading sna.cxt for 5.1.0 Cadence version.
sna.cxt for 5.1.0 Cadence version was successfully loaded
Loading lo.cxt
Loading techComp.cxt
INFO: Adding Substrate AC Analysis into Assura Menu
Sonnet 17:25 08-Jul-2011: Initializing forms and dialog boxes.
*INFORMATION* Sonnet 17:25 08-Jul-2011: Default Substrate File "/disk/usr/mkobasa/Sonnet/mat1/use_gpdk180.mat1" will be used.
Sonnet 17:25 08-Jul-2011: Read Substrate file: "/disk/usr/mkobasa/Sonnet/mat1/use_gpdk180.mat1".
Loading schematic.cxt
Sonnet 17:25 08-Jul-2011: Loading Sonnet properties from the cell view.
Sonnet 17:25 08-Jul-2011: Read Substrate file: "/disk/usr/mkobasa/Sonnet/mat1/gpdk180.mat1".
Sonnet 17:26 08-Jul-2011: The Spectre S-Parameter Model file "/disk/usr/mkobasa/cadence/virtuoso/oa/testcadence0A/testfiles/u
Sonnet 17:26 08-Jul-2011: The Touchstone S-Parameter Model file "/disk/usr/mkobasa/cadence/virtuoso/oa/testcadence0A/testfile
Sonnet 17:26 08-Jul-2011: SnpFile set as /disk/usr/mkobasa/cadence/virtuoso/oa/testcadence0A/testfiles/use_gpdk180_balun2_Son
Sonnet 17:26 08-Jul-2011: Setup Security for cvbridge.
Sonnet 17:26 08-Jul-2011: Done Setup Security for cvbridge.
Sonnet 17:26 08-Jul-2011: Cadence Virtuoso Interface license (cvbridge) has been checked out.
Sonnet 17:26 08-Jul-2011: Execute Process Sonnet Em was successful.
Checking project for pre-existing data.
Initializing frequency sweep combinations.
Subsectioning circuit.
Subsectioning time: 12 seconds.
Preparing calibration standards
Circuit requires 13671 subsections (428619 CM Cells) and 1466 MB of memory.
1 GHz Analyzing primary
Threads: using 8 thread(s), 8 core(s) available.
Waveguide mode time: 0 seconds.
Loading matrix (step 1 of 105)
  
```

Cadence Interface

The image displays the Sonnet Cadence Virtuoso Interface, which is used for electromagnetic simulation. The main window shows the design configuration for a balun. The design parameters are as follows:

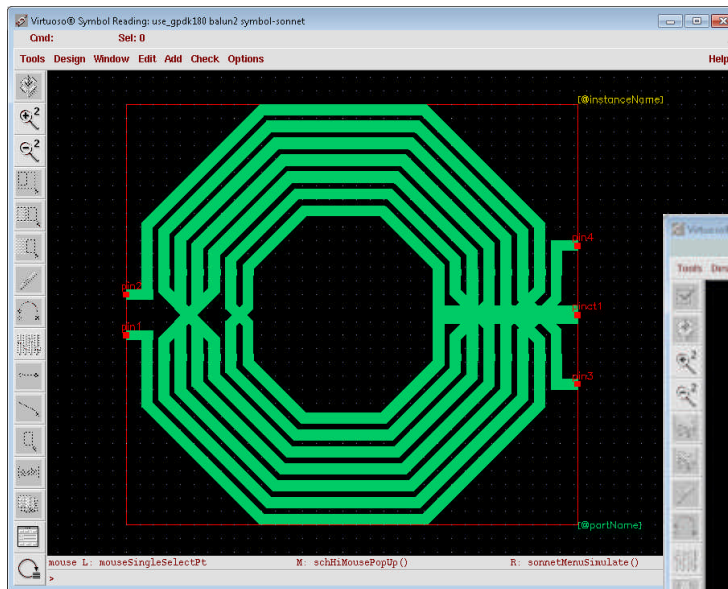
Library	Cell	View
use_gpdk180	balun2	SonnetEM

The Sonnet Frequencies table is also visible:

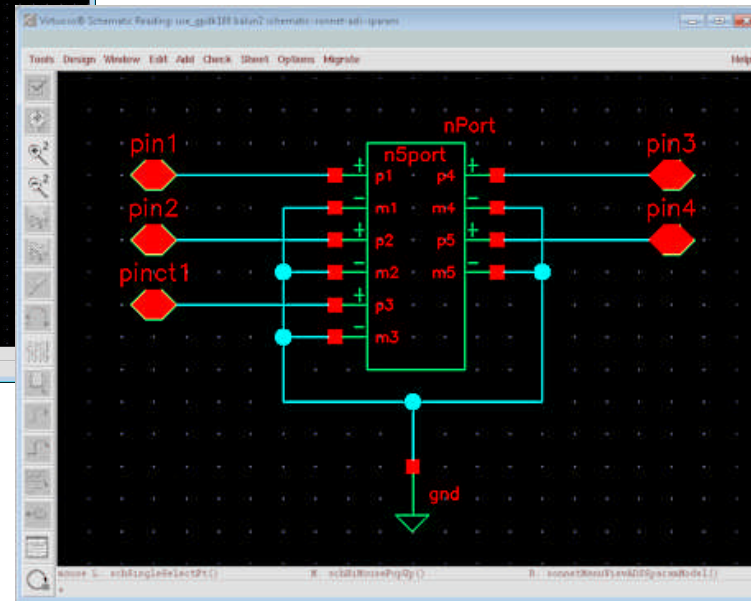
#	Type	Range
1	Single	1 GHz
2	Single	5 GHz
3	Single	8 GHz
4	ABS	0.01 GHz to 80 GHz
5	DCPoint	0 GHz Automatic 1798.754748 KHz

The interface also shows a Sonnet Current Density Viewer window displaying a color-coded plot of the current density on the balun structure. A Sonnet Response Viewer window is overlaid, showing a Cartesian plot of Inductance (nH) and Q Factor versus Frequency (GHz). The plot shows two curves: a blue curve for Inductance and a pink curve for Q Factor. The Inductance curve starts at approximately 2.5 nH at 0 GHz, dips to about 1.1 nH at 1 GHz, and then rises to a peak of about 2.8 nH at 16 GHz. The Q Factor curve starts at approximately 0.5 at 0 GHz, peaks at about 4.5 at 8 GHz, and then drops to about 0.5 at 16 GHz.

Cadence Interface



use results in schematic

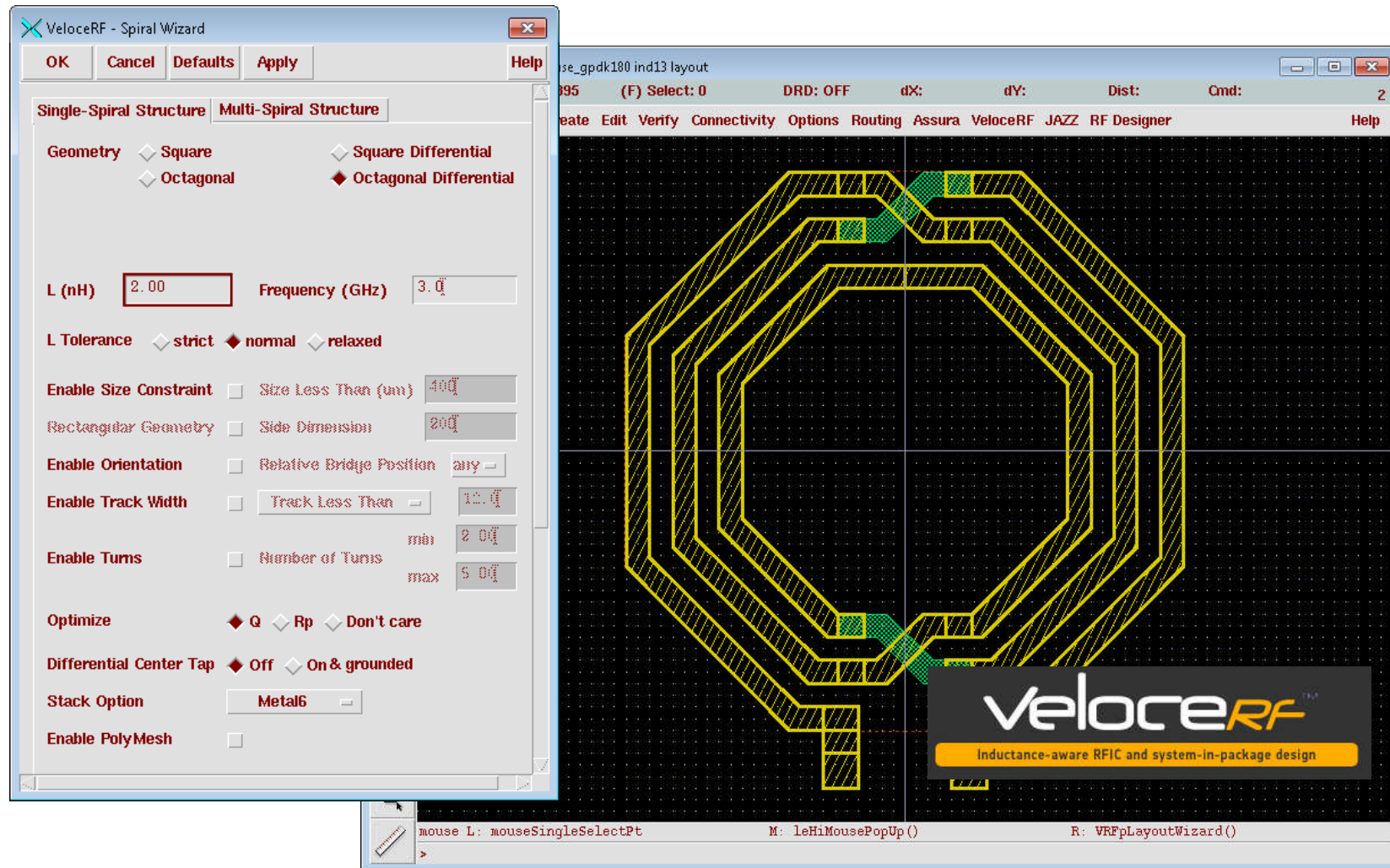


layout look alike symbol
is available

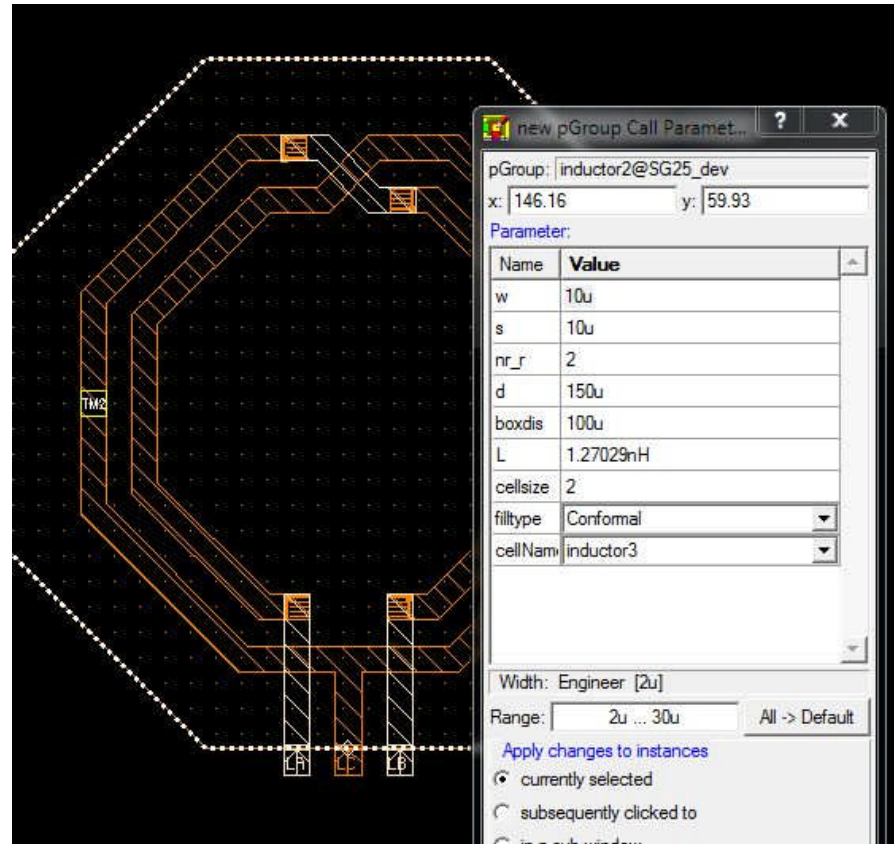
What Layout ?

- Sonnet can do the high precision EM analysis of an existing layout, but where do we get the layout from?
- Initial layout can be from:
 - Helic veloce RF inductor synthesis & parametric inductor library
 - Inductor pcell from design kit
 - Mühlhaus Spiral Inductor Assistant (Sonnet model generator)
 - other layout source

Helic VeloceRF



Designkit inductor pcell



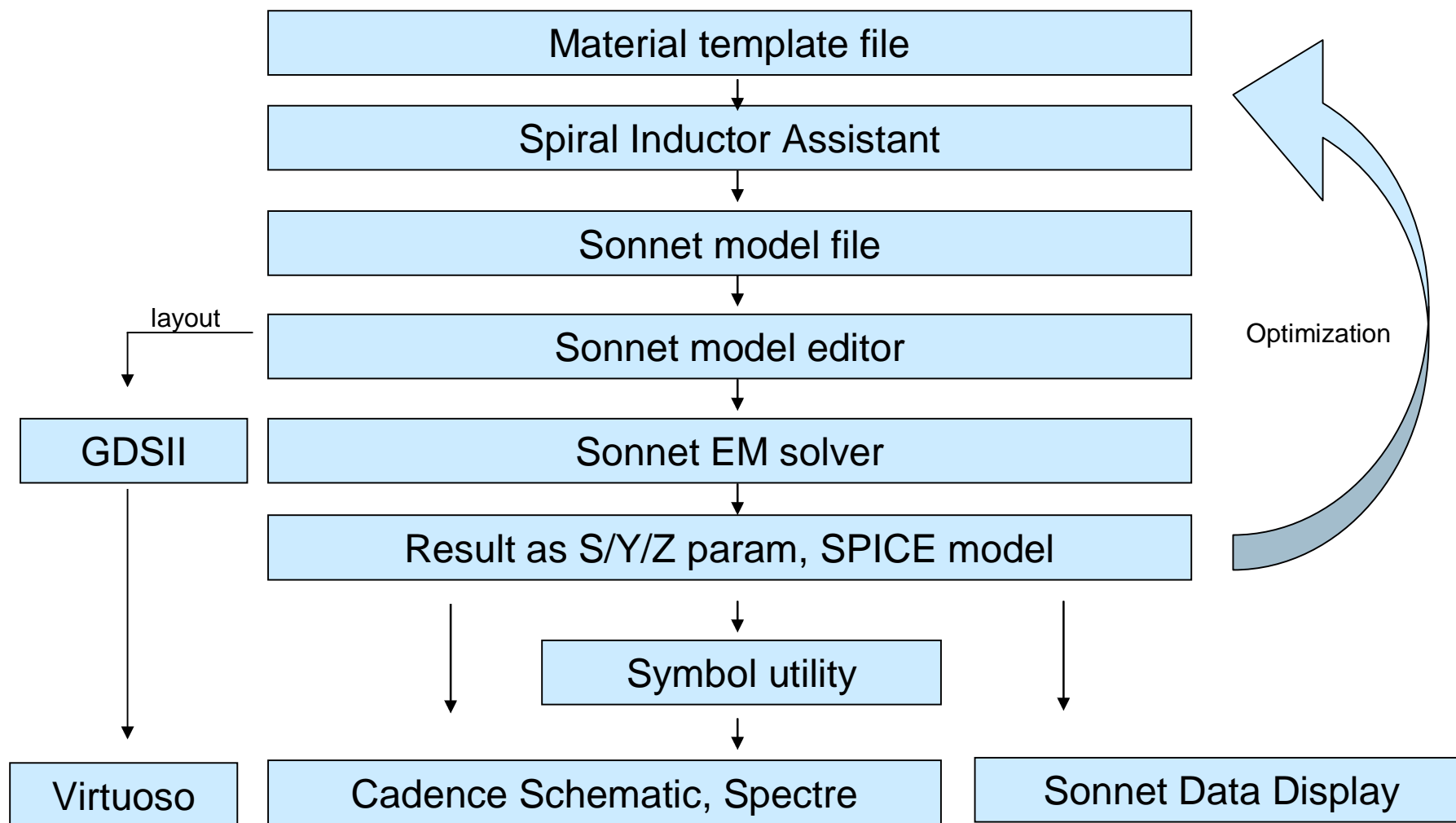
Mühlhaus Spiral Inductor Assistant

Sonnet inductor model generator

Metal Layer	Function	Diel. Layer	Thickness	Erel	Diel. Loss Tan	Diel Cond.	Mrel	Magn. Loss Tan
- 0 -	Lossless	none	2000um	1	0	0	1	0
- 1 -	Lossless	none						
- 2 -	M1	spiral	2um	3.9	0	0	1	0
- 3 -	M2	bridge	1um	3.9	0	0	1	0
- 4 -	Lossless	none	2um	3.9	0	0	1	0
		Oxide above M1	2um	3.9	0	0	1	0
		Oxide at M1	1um	3.9	0	0	1	0
		Oxide between M1 M2	2um	3.9	0	0	1	0
		Oxide below M2	2um	3.9	0	0	1	0
		Substrate	300um	11.9	0	5	1	0



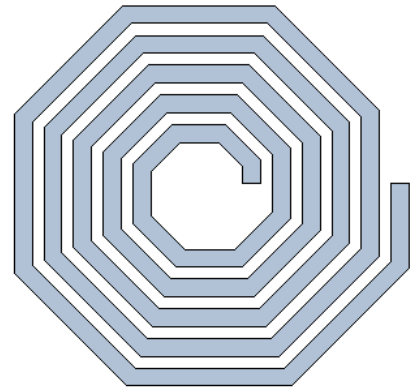
Mühlhaus Spiral Inductor Assistant



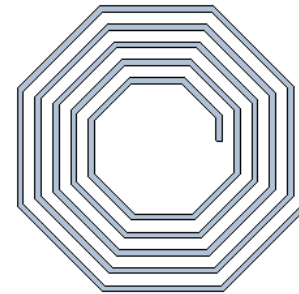
Example: 5nH Inductors compared

(only top metal layer is shown here)

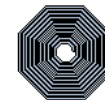
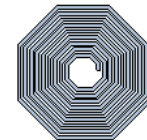
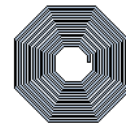
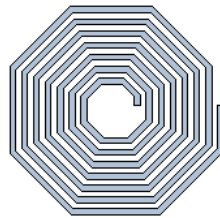
$n=5$ $w=15\mu\text{m}$
 $s=10\mu\text{m}$ $r=50\mu\text{m}$



$n=5$ $w=5\mu\text{m}$
 $s=10\mu\text{m}$ $r=40\mu\text{m}$



$n=7$ $w=5\mu\text{m}$
 $s=5\mu\text{m}$
 $r=20\mu\text{m}$

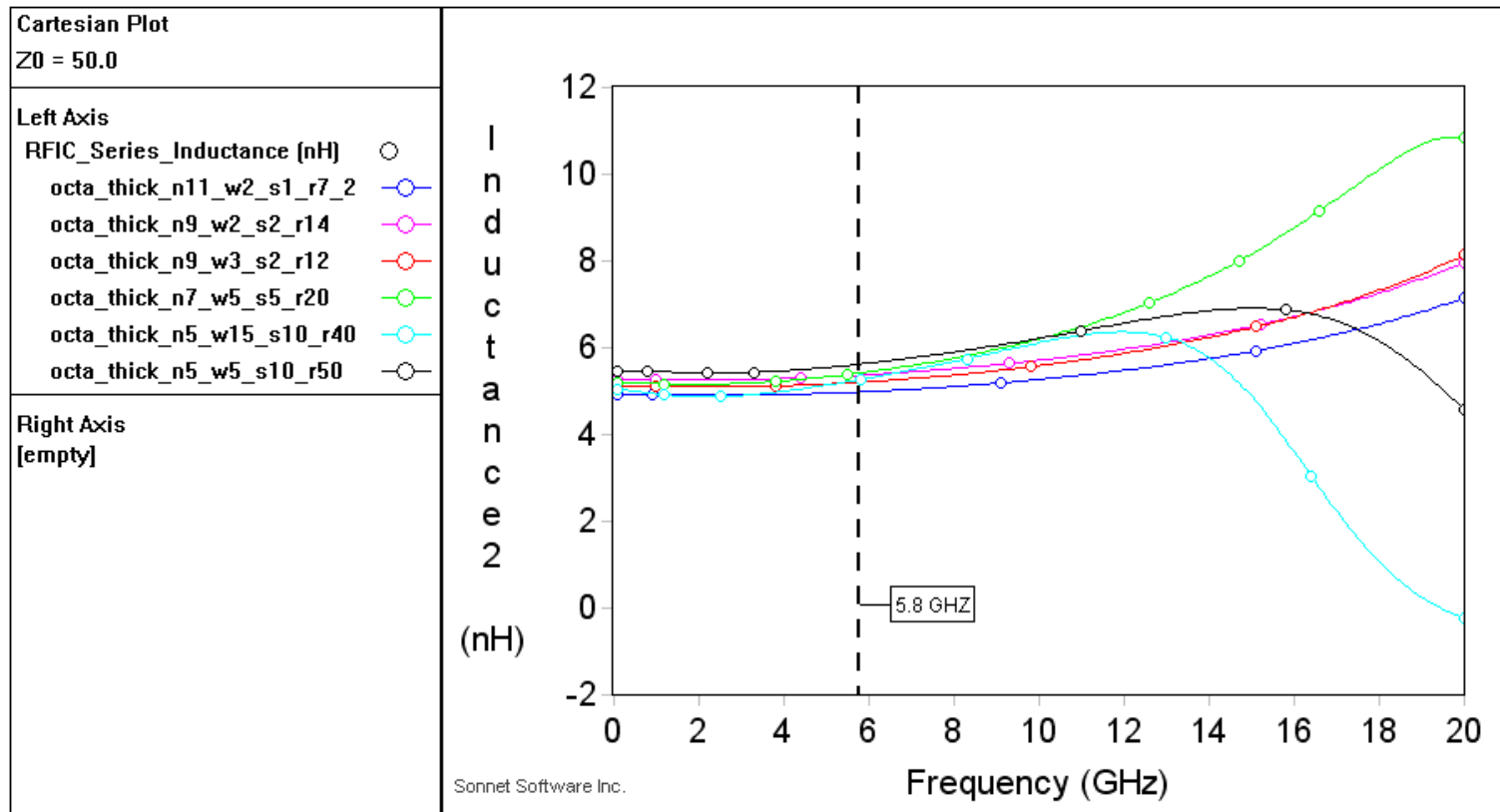


$n=11$ $w=2\mu\text{m}$
 $s=1\mu\text{m}$
 $r=7\mu\text{m}$

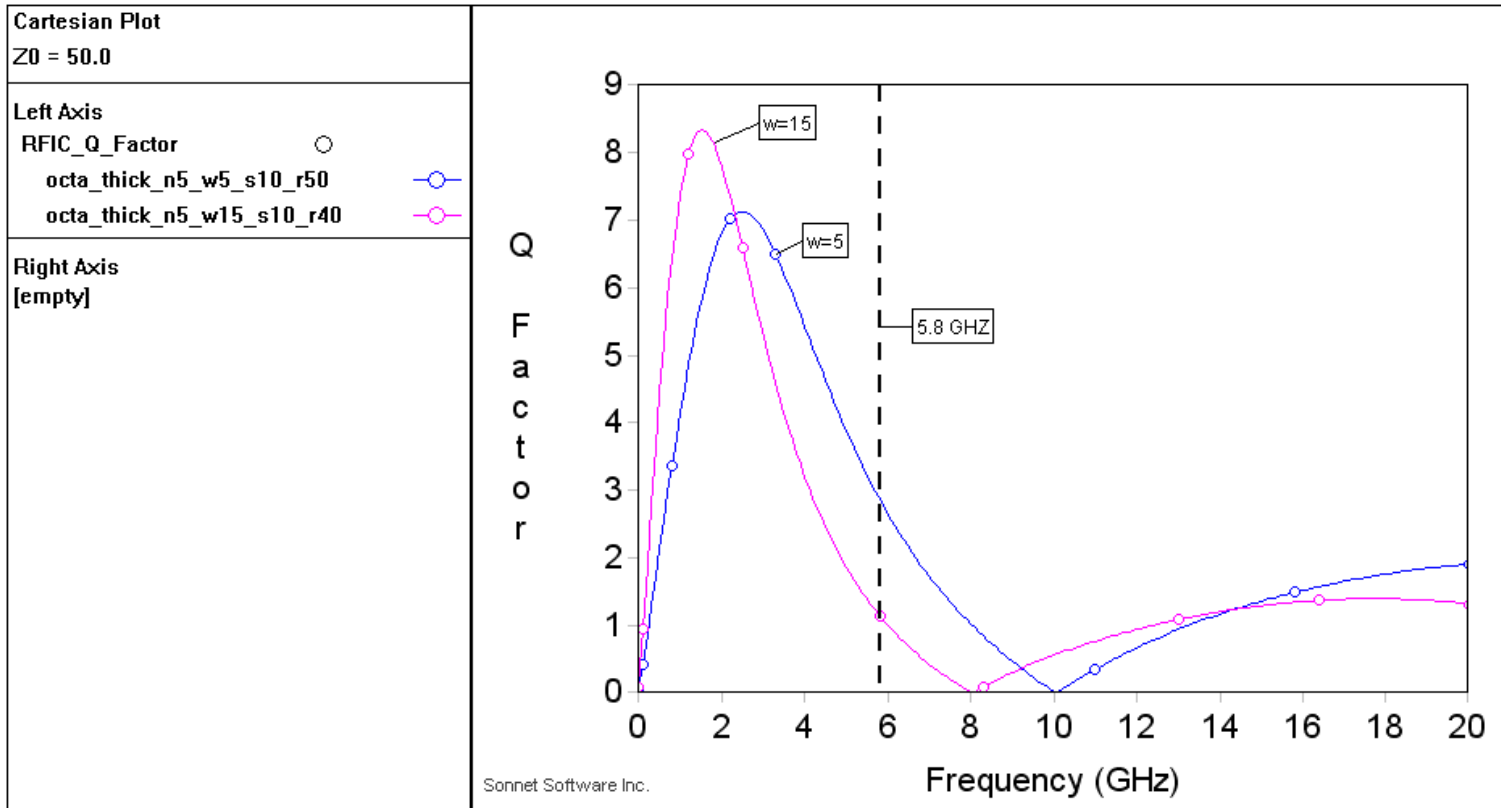
$n=9$ $w=2\mu\text{m}$
 $s=2\mu\text{m}$
 $r=14\mu\text{m}$

$n=9$ $w=3\mu\text{m}$
 $s=2\mu\text{m}$
 $r=12\mu\text{m}$

Inductance



Q Inductor with N=5

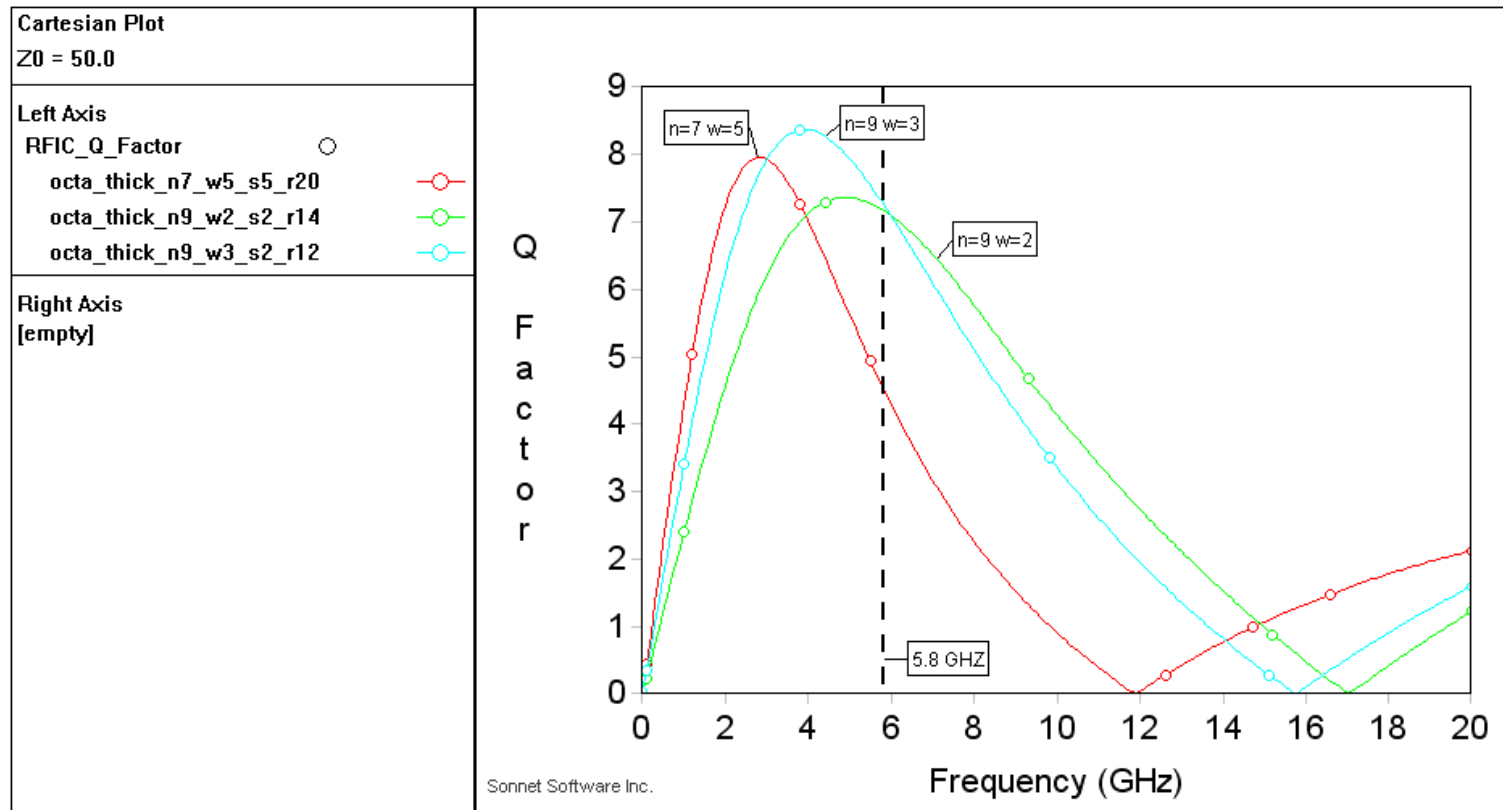


$w = 5\mu\text{m} \dots 15\mu\text{m}$

$f(Q_{\text{max}})$ too low

- too much shunt capacitance
- reduce line width and/or move lines up, away from the substrate

Q Inductor with N=7 and N=9

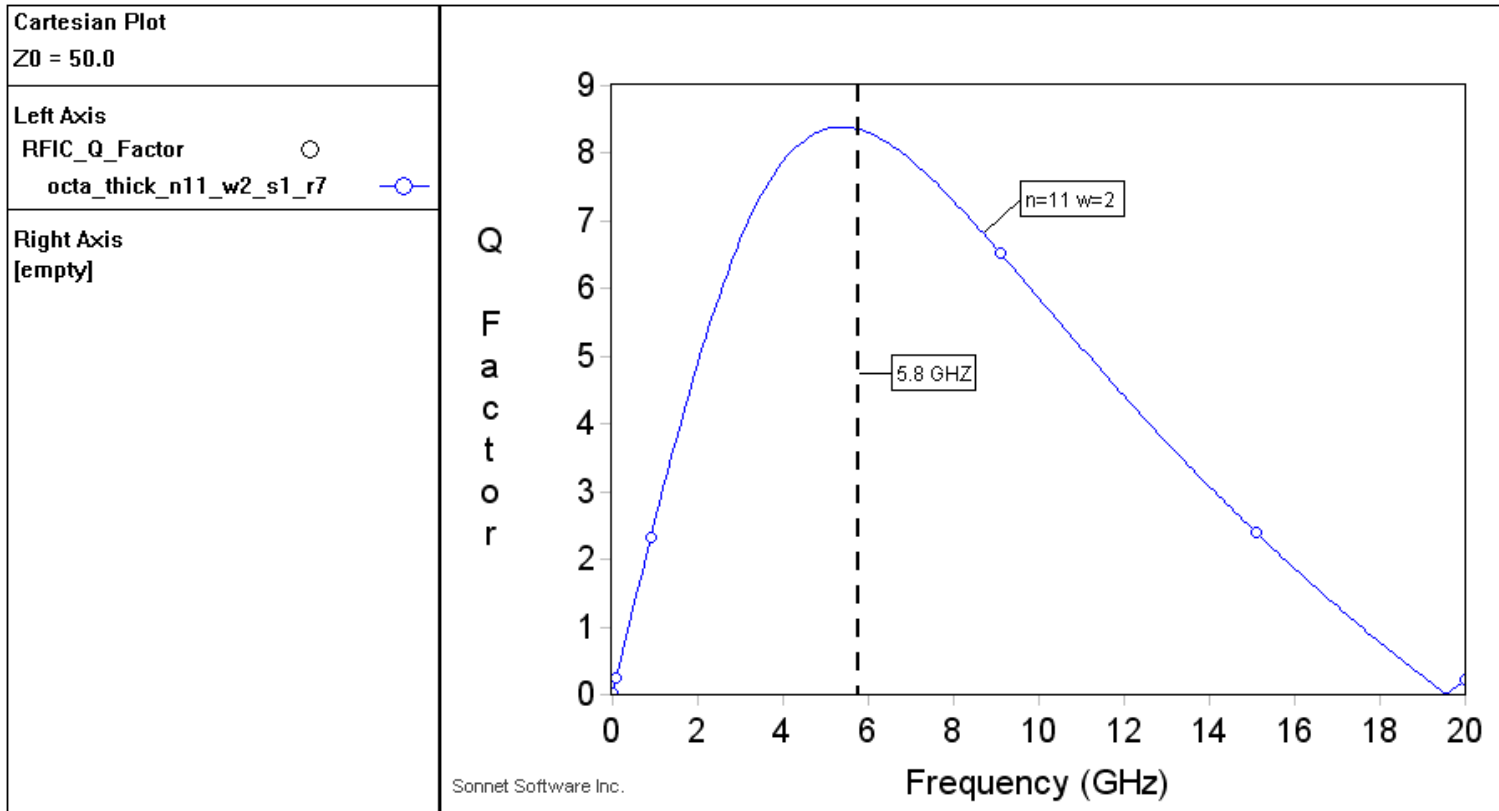


$w = 2\mu\text{m} \dots 5\mu\text{m}$

$f(Q_{\text{max}})$ too low

- too much shunt capacitance
- reduce line width and/or move lines up, away from the substrate

Q Inductor with N=11

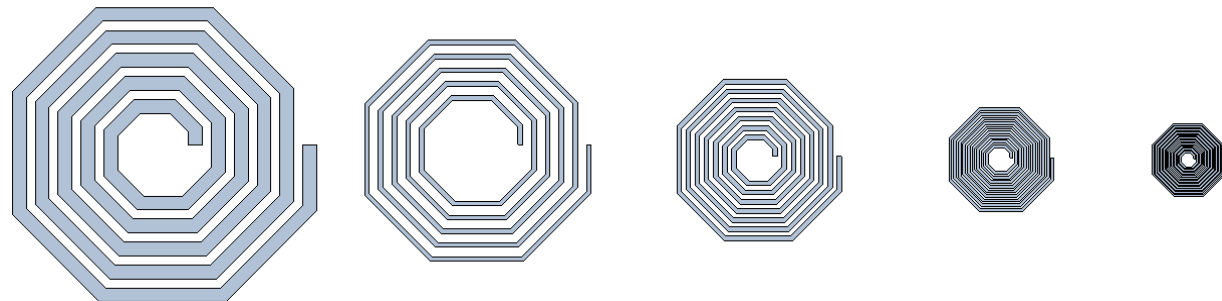


$w = 2\mu\text{m}$

Spacing = $1\mu\text{m}$ is critical, check for possible design rule violation

Summary 5nH Inductors

	N=5	N=5	N=7	N=9	N=11
Width	15 μ	5 μ	5 μ	3 μ	2 μ
Spacing	10 μ	10 μ	5 μ	2 μ	1 μ
Inner radius	40 μ	50 μ	20 μ	14 μ	7 μ
Outer Diameter	333 μ	248 μ	180 μ	115 μ	81 μ
$f_{Q_{max}}$	1.5 GHz	2.5 GHz	2.8 GHz	3.9 GHz	5.5 GHz
Q @ 5.8GHz	1.1	2.9	4.5	7.2	8.3
R_{DC}	3.3 Ω	8.0 Ω	7.2 Ω	9.2 Ω	11.9 Ω



Need more automation?

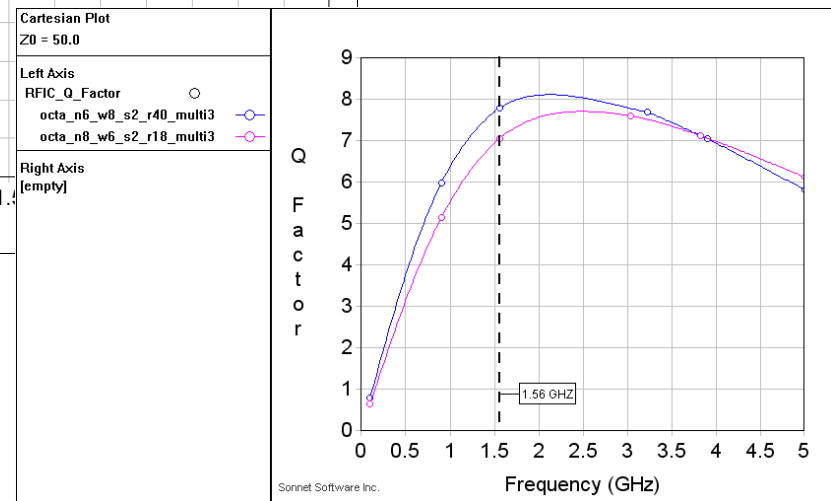
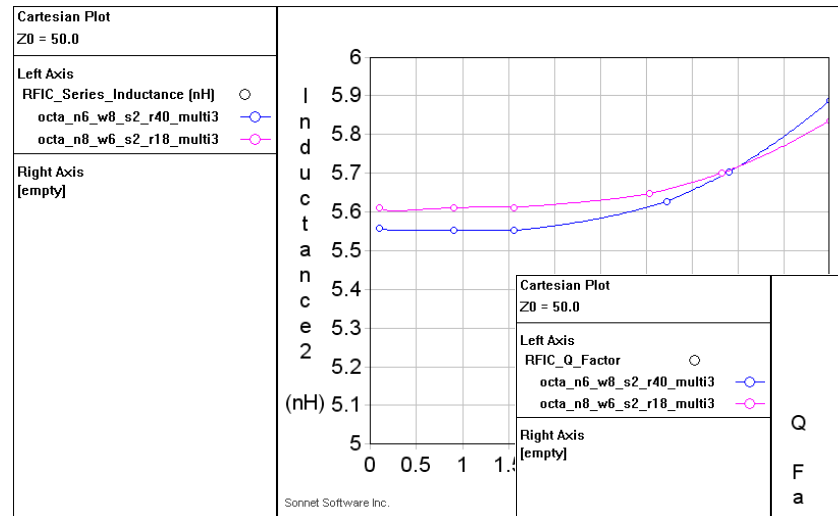
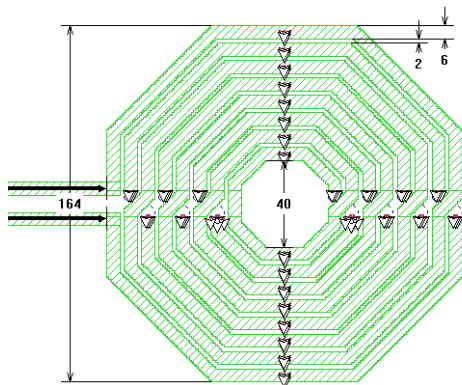
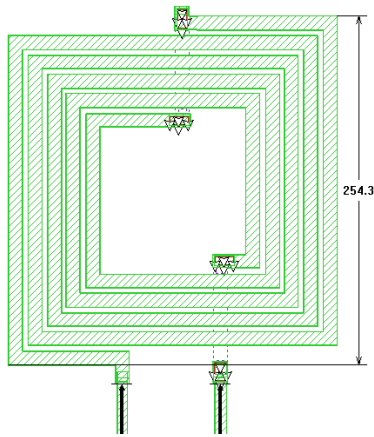
- If you need more automation in finding the best inductor layout, tools like Helic Veloce RF are for you
- Once you have selected a layout, Sonnet is the best choice for high precision EM analysis of that layout, with "silicon accurate" results

Want more flexibility?

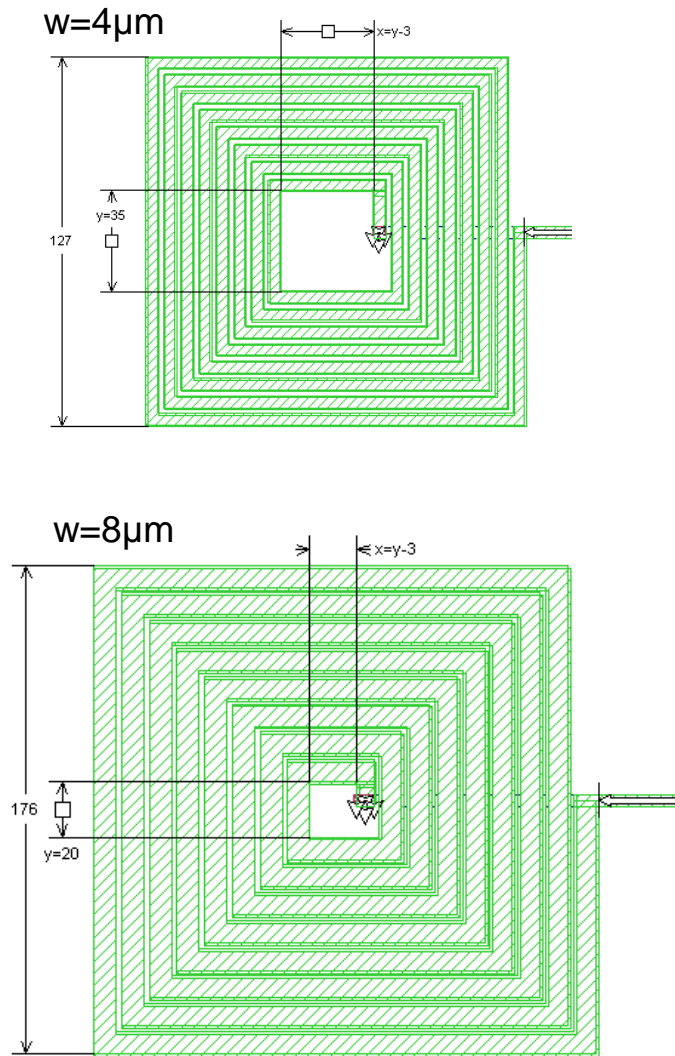
- For users who have become familiar with the Sonnet EM solver, the Sonnet editor offers additional possibilities:
- Use parameters and equations for geometries
- Sweep material properties for worst case/sensitivity test
- Analyze coupling between inductors
- Analyze transmission line structures
- Analyze geometry details at transistor level

Geometry Parameter Sweep

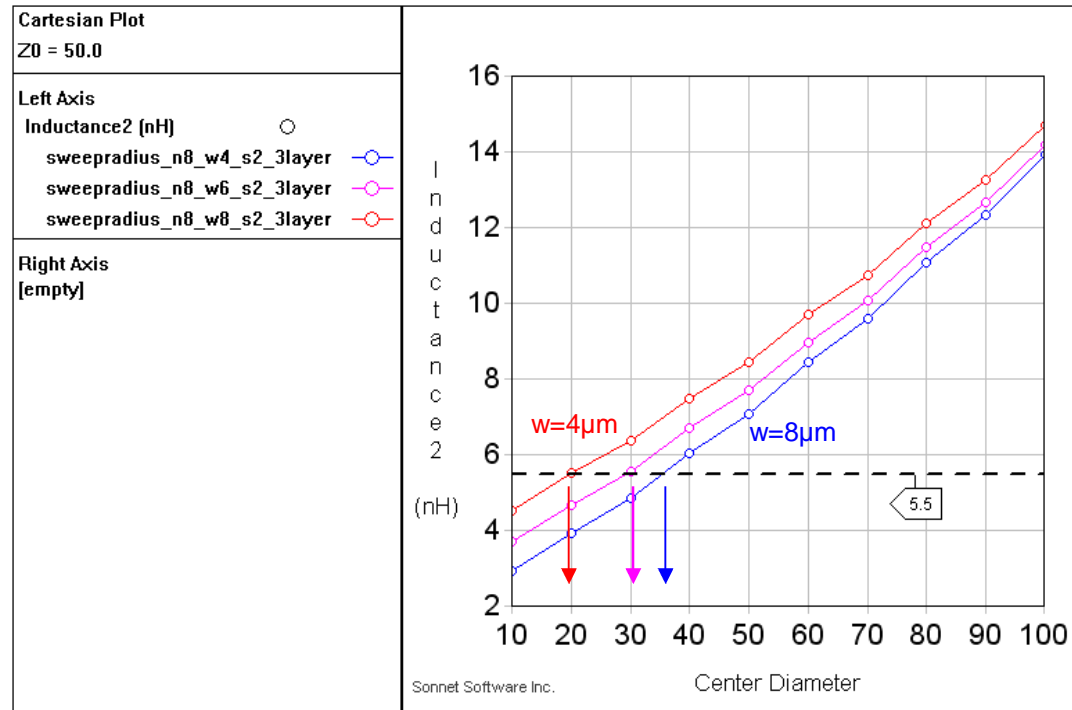
- Get simulated S-Params
- L, Q, series resistance, substrate cap, ...
- Broad band model file



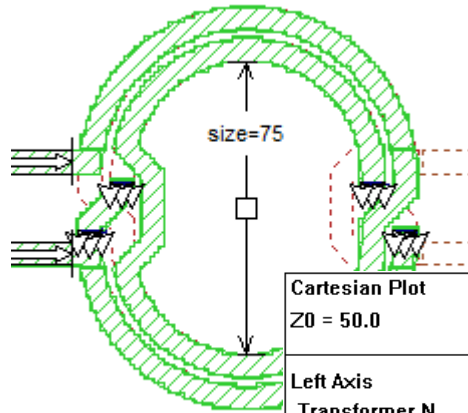
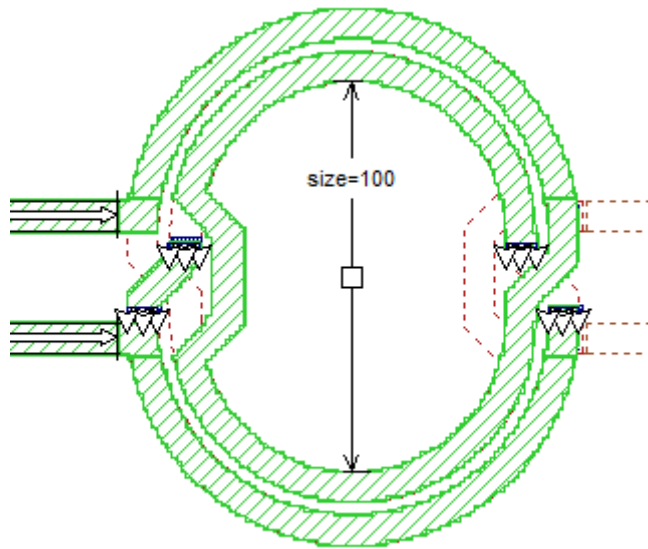
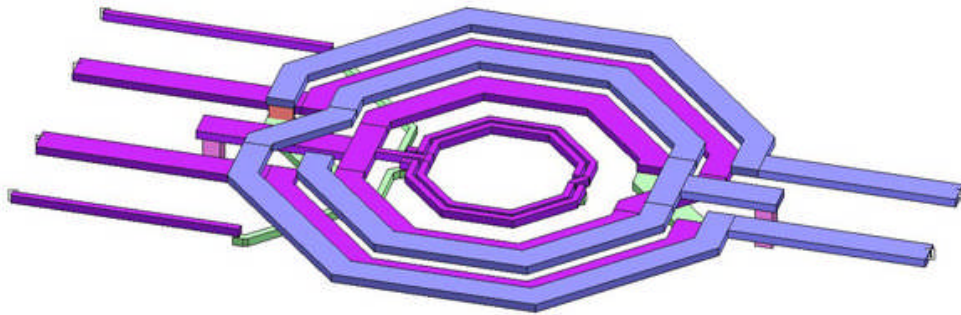
Geometry Parameter Sweep



Inductance vs. center diameter

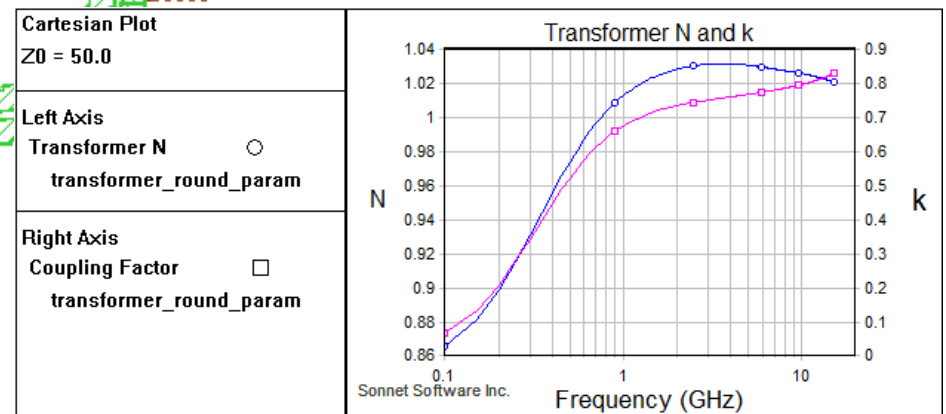


Transformers



Equation Management

Equation
Coupling Factor
Inductance1 (nH) from Z11/Z22
Transformer N
* Inductance1 (nH)
* Inductance2 (nH)
* Capacitance1 (nF)



Summary

- Customized inductors have advantages over standard parts from the design kit library
- For reliable design of inductors, we need a high precision EM solver with silicon accurate results.
- For efficient design of inductors, a workflow is needed that includes layout generation, EM analysis and model generation.
- *No guru needed:*
Sonnet combines ease of use for "normal users", additional capabilities for expert users and very accurate, reliable simulation results for first pass success.

References & Resources

- **Sonnet for RFIC overview**
<http://muehlhaus.com/products/sonnet-planar-3d/sonnet-for-integrated-circuit-design-and-verification>
- **Sonnet for RFIC application notes**
<http://muehlhaus.com/support/sonnet-application-notes>
- **Sonnet Cadence interface**
http://www.sonnetsoftware.com/products/sonnet-suites/ef_translators_cvbridge.html
- Gerhard Metzger-Brückl, Christophe Holuigue, Volker Mühlhaus,
" **Optimization of a RF CMOS technology for High-Q-Inductors**", MOS-AK Athens 2009
- Falk Korndörfer, Mehmet Kaynak, Volker Mühlhaus,
" **Simulation and Measurement of Back Side Etched Inductors**",
presented at EuMC/EuMIC01-4, European Microwave Week, 28 Sept 2010
- [Sidina Wane, James C. Rautio and Volker Mühlhaus, "Topological and Functional Partitioning in EM Analysis: Application to Wafer-Level Chip-Scale Harmonic Filters," IEEE IMS, 2009](#)
- [David I. Sanderson, James C. Rautio, Robert A. Groves, and Sanjay Raman, "Accurate Modeling of Monolithic Inductors Using Conformal Meshing for Reduced Computation," Microwave Magazine, Vol. 4, No. 4 December 2003, pp. 87 - 96](#)

Thank You!

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volker@muehlhaus.com