Automatic Model Extraction for RFIC Spiral Inductors Using SonnetLab

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External Use

Agenda

- Introduction
- Inductor model Extractor (IME)
- Automatic inductor modeling example
- Conclusions

Introduction

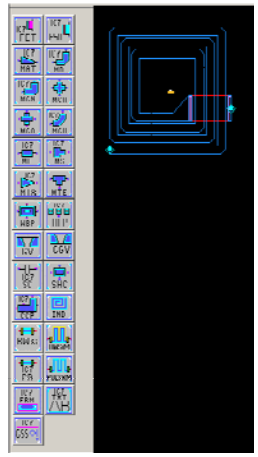
- Design space exploration is important in RFIC design.
- To enable first pass success in the design of experiments (DOE), parameterized models for RFIC components are needed.
- Fast and accurate models are required for rapid design optimization.

RF Modeling Team at Freescale

- The RF Modeling Team at Freescale is responsible for design kit development for CAD-based design.
- A design kit contains a list of components corresponding to a specific technology in different forms.
  - Schematic models for circuit-level simulation and performance optimization.
  - Component artworks for layout design and EM-level simulation.
  - Substrate definition, layer definition, DRC, etc.
- Number of requests for new design kits has been increased dramatically as the CAD-based design flow becomes standard.

Motivations

- Design kit modeling challenges:
  - Models before wafer.
  - Multiple design kits developed in a short time.
  - Conventional design kit modeling is highly resource driven.
- Need an efficient solution to meet the demands.
  - Simulation-based modeling approaches.
  - Fully computerized modeling with minimal engineer interaction.
  - Reduced modeling cost in both time and resources.
- *Automatic model generation is desired!*



Design-kit

Automation in Design Kit Modeling

- Typical design kit modeling:
  - Develop models that accurately represent the component behaviors for a specified technology.
  - A modeling problem involves:
    - Component data generation from simulation or measurement.
    - Model extraction procedure to fit model to data.
- Our automatic modeling for design kit development:
  - Automatically generate component models with EM-level accuracy and fast simulation speed.
  - Automate modeling process from data generation, model selection, to model extraction.
  - Utilize physics-based formulation, if available, to reduce modeling complexity and obtain most compact model with good generalization capability.

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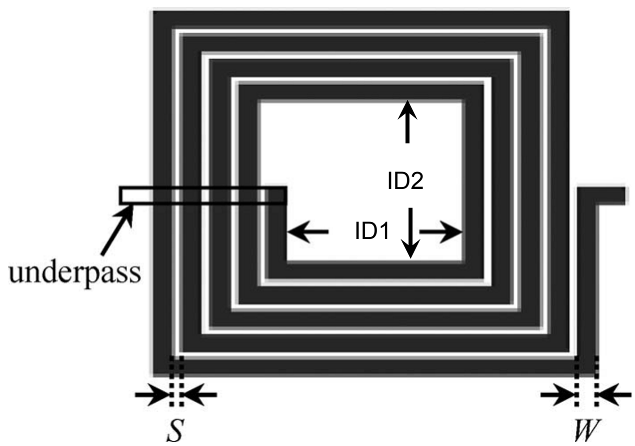
RFIC Inductors

- Integrated spiral inductors are widely used in RFIC circuit as matching elements, whose design is important for the circuit performance.
- The physical structure of a spiral inductor is usually determined by number of turns, the line width of the coils, the spacing between the coils, and the diameters.
- Because of this high dimension in its physical space, parameterized modeling of the spiral inductor could be a challenge to fully represent its behavior in a given design space.

Layout of A Rectangular Spiral Inductor



Geometrical inputs:
Line width *W*, number of turns N, Inner diameter ID1, ID2, Spacing S.

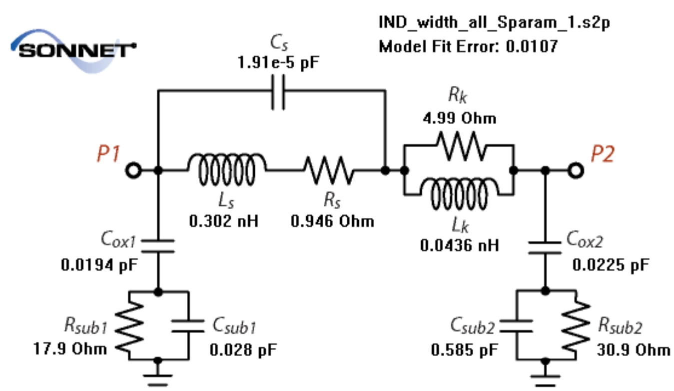
Challenges for Modeling RFIC Inductors

- Measurement-based modeling approach usually requires hundreds of different inductors to cover the design space.
- It is usually time-consuming and impractical to manually develop models for many inductors in a design space.
- A parameterized model is needed to fit every set of measurement data.
  - It is desired to use one frequency-independent equivalent circuit topology to cover a wide range of inductors.
  - However, the EC component values vary according to the change in the dimension of the inductor.
  - How to find a mathematical mapping from the geometrical dimensions to the EC component values is not trivial.

Inductor Model Extractor (IME) from Sonnet™

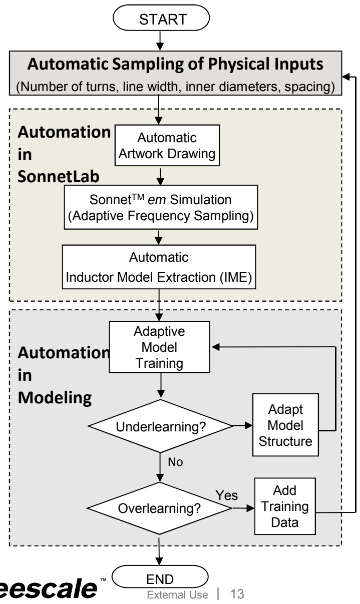
- EM-simulation based modeling has become popular.
  - EM-based simulations can replace the human-intensive measurement effort.
  - It can produce comparable accuracy to measurements.
- Sonnet™ is a commercial EM simulation tool and has a new feature of Inductor Model Extractor (IME), which can generate an intuitive equivalent circuit based on the EM analysis results.
  - The tool is available from both Sonnet™ GUI and SonnetLab Toolbox for MATLAB®.
  - It extracts an enhanced PI network from the EM simulation results.
- This enables automation of the previous manual modeling procedure, from data generation to extraction of the equivalent circuit models.

Advanced PI Model Topology in IME



- Sonnet™ has two topologies available for the model: Untapped and Center Tapped.
- This work uses the Untapped topology shown above.
- For more information about both topologies, visit: http://www.sonnetsoftware.com/products/sonnet-suites/ef_ime.html.

Automatic Model Generation (AMG) Flow

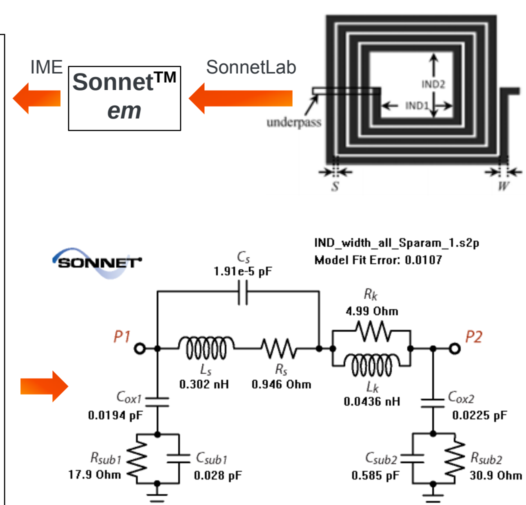


- AMG stages:
  - Automatic sample selection by adaptive sampling
  - Automatic data generation by setting up simulator driver
  - Automatic model development

Lei Zhang and Peter Aaen, "Automatic modeling of passive components for RFIC circuit design using SonnetLab", *ACES Conference, EM Applications in Sonnet*, Monterey, CA, March 2013.

Illustration of Automation in SonnetLab

```
simulator lang=spectre
subckt IND_width_all_Sparam_1 1 4
L_1 1 2 inductor l = 0.302e-9
R_2 2 3 resistor r = 0.946
C_3 1 3 capacitor c = 1.91e-17
L_4 3 4 inductor l = 0.0436e-9
R_5 3 4 resistor r = 4.99
C_6 1 5 capacitor c = 0.0194e-12
R_7 5 0 resistor r = 17.9
C_8 5 0 capacitor c = 0.028e-12
C_9 4 6 capacitor c = 0.0225e-12
R_10 6 0 resistor r = 30.9
C_11 6 0 capacitor c = 0.585e-12
ends IND_width_all_Sparam_1
```



SonnetLab Scripts

- Start a new Sonnet^{TM} project:

  Project=SonnetProject();

  Project.saveAs(SonnetProjectName);

- Add a dielectric layer:

  Project.addDielectricLayer('cap_nitride',0.15, 7.5, 1.0, 0, 0.0, 0);

  Project.addDielectricLayer('thkM5',3.0, 4.3, 1.0, 0, 0.0, 0);

- Add a material:

  Project.defineNewThickMetalType('metal5',2.778e7,0,3.6,2);

  Project.defineNewResistorMetalType('polyres',69);

- Add a metal polygon:

  Project.addMetalPolygonEasy(1,[0;TL+3;TL+3;0],[BoxSizeY/2+Port1_Width/2+2;BoxSizeY/2+Port1_Width/2+2;BoxSizeY/2-Port1_Width/2-2;BoxSizeY/2-Port1_Width/2-2],'metal5');

- Add a frequency sweep:

  Project.addAbsEntryFrequencySweep(0.5,12);

- Add an output file:

  Project.addFileOutput('DATA_BANK','D','Y','FSL_IND.s2p','NC','Y','S','RI','R',50);

- Add IME output file:

  Project.addINDModel('D','Y','FSL_IND.net','IC','Y','SPECTRE','Y','SKIN_EFFECT','AUTO')

- Simulate in Sonnet^{TM} *em:*

  Project.simulate('-c -s C:\Program Files\Sonnet Software\14.52');

Automatic Model Development

- Automatic modeling is the procedure to adaptively find the best compact model to fit the component data thus accurately represent its behavior.
- A variety of model forms are available in AMG tools, such as neural networks, polynomial/rational functions, spline models, support vector machines, etc.
  - These models are more like a black box and lack inside physics of the component to be modeled.
- Incorporate pre-knowledge such as known physics or equivalent circuit topology can reduce the modeling complexity and data samples.

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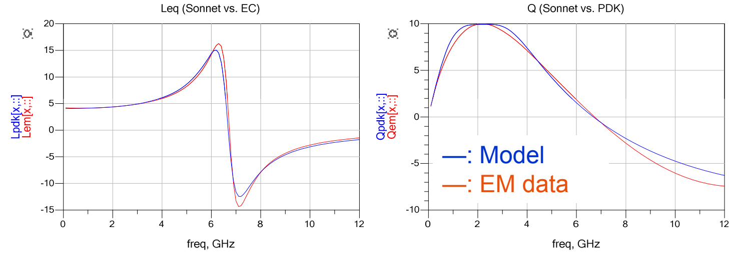
Parameterized Modeling of A Rectangular Inductor

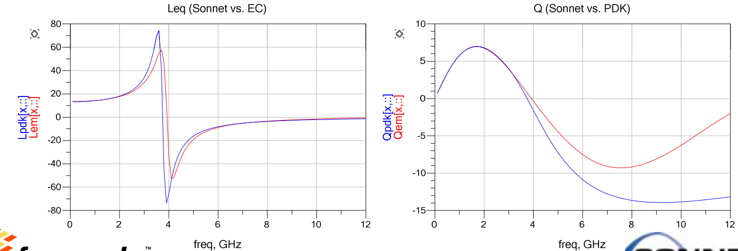
- Design space of the rectangular spiral inductor to be modeled:
  - Number of turns: 1 to 5 with quarter turn increment
  - Line Width: 5~25 μm
  - Inner diameters: 25~250 μm
  - Spacing: 5 μm
- Adaptive sampling diagram generated 806 inductors in the design space and sent them for EM simulations in Sonnet™.
- IME tool was invoked to extract every simulated S-parameter set to an equivalent circuit model.
- A table look-up model with near points interpolation is used to map the physical design parameters to the EC parameters.

Comparison of L and Q for Two Inductors

Inductor 1: Nturns = 4, line width = 15 μm, ID1 = 70 μm, ID2 = 200 μm



Inductor 2: Nturns = 5, line width = 5 μm, ID1 = 250 μm, ID2 = 250 μm



Comparison of the L and Q for 100 Inductors

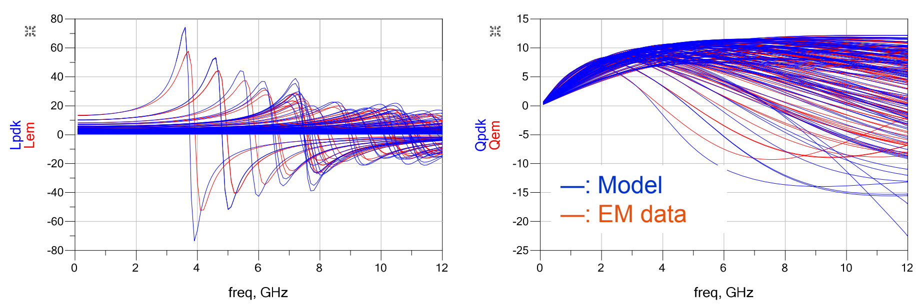
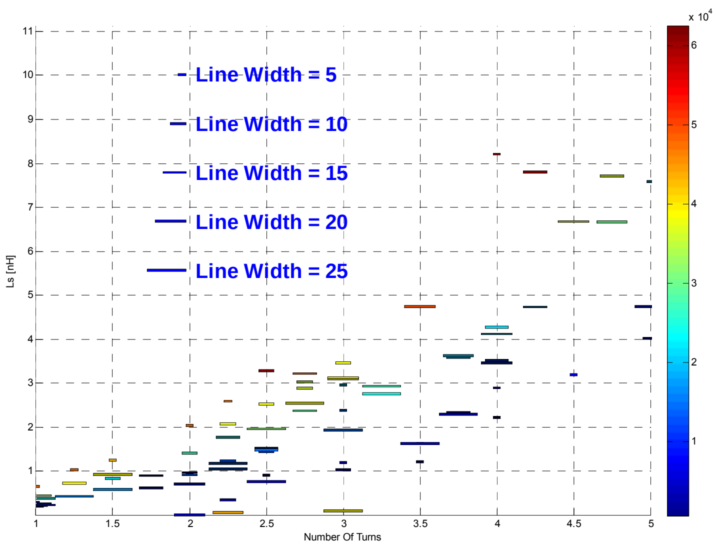


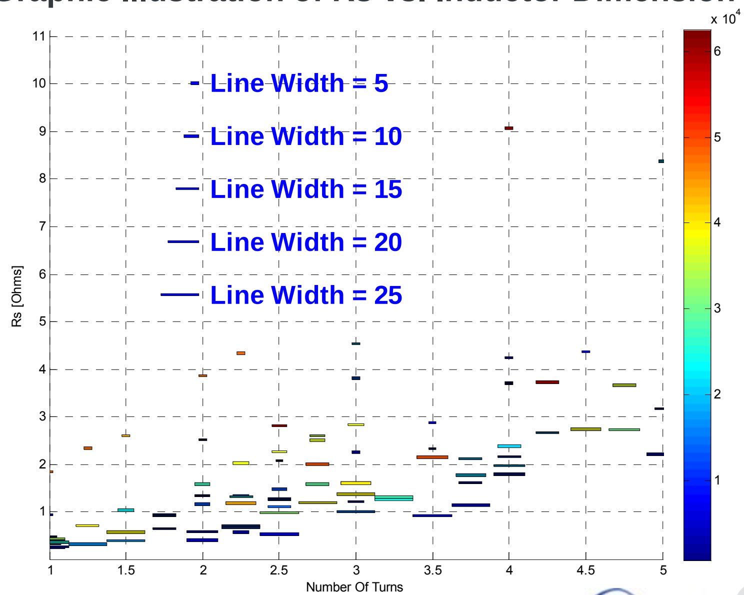
Table Representation of the IME Extracted Model

Nturns	Line Width (µm)	ID1 (µm)	ID2 (µm)	Ls (nH)	Rs (Ohm)
1	15	250	97	0.009233	0.529786
2	20	56	56	0.010375	0.402145
3	10	250	143	0.10497	2.81627
1	20	250	201.5	0.530292	0.510291
2.5	15	46	46	0.532232	0.568558
2.5	15	148	97	1.43693	1.09358
⋮	⋮	⋮	⋮	⋮	⋮
5	5	194	250	10.884	10.6906
15	2.25	148	148	1.42512	1.09144
25	3.5	158	250	4.08652	1.67542

A Graphic Illustration of Ls vs. Inductor Dimension



A Graphic Illustration of Rs vs. Inductor Dimension



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Conclusions

- We presented the application of Sonnet^{TM}'s IME tool for EM-simulation based automatic modeling of RFIC spiral inductors.
- Inductor models with EM-level accuracy can be automatically generated through MATLAB® scripted modeling routines.
- Efficient parameterized modeling of a rectangular spiral inductor was demonstrated and good model accuracy was observed.
- This automatic modeling flow enables fast model development with minimum engineer resources, compared to the measurement-intensive manual modeling.

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