

Simple DOE-based inductor tool for design automation

K. Kwok, Shing Lee*, Rui Lin, P. Zampardi

Skyworks Solutions, Inc., 2427 W. Hillcrest Drive, Newbury Park, CA 91320

*Peregrine Semiconductor, 9380 Carroll Park Drive, San Diego, CA 92121

kai.kwok@skyworksinc.com, 805.480.4483

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Abstract

We present the development of an inductor tool that allows designers to correlate between the geometrical dimensions and the electrical properties of a spiral inductor. We have demonstrated that using a DOE approach and EM simulations only a relatively small set of inductor test structures needs to be measured for validating this inductor tool that accurately predicts the inductor electrical properties. The implementation of this inductor tool in the circuit simulator for design automation is discussed.

INTRODUCTION

On-chip spiral inductors are used to realize matching networks in RF circuitry. However, due to the lack of accurate analytical expressions for important electrical properties (such as the quality factor and resonance frequency) in terms of the geometrical dimensions (track width, spacing, number of turns, inner hole dimensions), describing these inductors is challenging for both modeling and design automation. Traditionally, complicated equivalent circuit models [1] are provided as a solution to this challenge. However, they require sophisticated model development and extraction procedures as well as large set of measurement sets over a wide range of geometrical dimensions. Another option is to use electromagnetic (EM) simulations, which are computationally intensive and time-consuming, thus not yet practical for design automation.

From a practical design standpoint, the requirements of the trade-off between speed and accuracy are different in various design phases. Early in the design phase, it is advantageous to have a tool enabling the designers to easily select inductors by electrical properties and layout area at the expense of accuracy. This compromise in accuracy at the early phase is acceptable since the individual inductors will likely behave differently in the final circuit environment, where EM simulations are needed for verification anyway. Such a tool allows designers to quickly assess the impact of various component values and/or circuit topologies on the RF circuit performance before a more comprehensive simulation, of higher accuracy, is performed later in the design phase.

In this paper, we present a DOE (Design of Experiment) approach for developing an inductor tool in an efficient and

cost-effective manner. For predicting electrical properties of a spiral inductor (e.g. inductance L , quality factor Q , etc.) in terms of its geometrical dimensions (Fig. 1), the S-parameter measurement of only 25 inductor test structures is required. We shall discuss the DOE design, the analysis of the measured data of spiral inductors fabricated in Skyworks' InGaP HBT process, the accuracy of the property prediction, and the implementation of the inductor tool in the design environment.

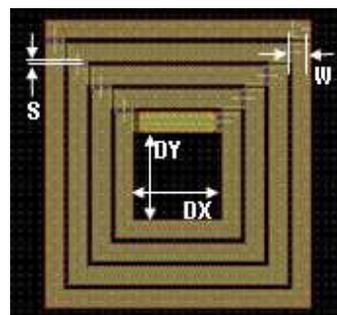


Figure 1. Layout of a 2-layer inductor where W is the track width, S the spacing, DX and DY the inner hole dimensions.

THE DOE APPROACH

The development flow of this approach is described by the following steps: 1) define the DOE space by determining the factors and their range, 2) select the DOE objective, design type, and model type, 3) generate the experiment worksheet and perform EM simulations for sanity check to ensure manufacturability and that the resulting electrical properties/responses cover the design space of interest, 4) build test structures, measure S-parameters, and validate EM simulator, 5) perform EM simulations over a larger set of inductor DOE, extract electrical properties from simulation results and perform RSM fitting for each electrical response.

Define DOE space. The rectangular-shaped spiral inductor in Figure 1 can be defined by five geometrical parameters: track width (W), spacing between tracks (S), number of turns (N), inner hole dimension in the horizontal axis (DX) and in the vertical axis (DY). For the purpose of validating the EM simulator, we can assume that DX and DY are the same. So, we define four factors (W , S , N , DX)

corresponding to the four geometrical parameters. The range of the factors is determined by considering the design rules of the semiconductor process and input from designers. The factor settings are listed in Table I.

TABLE I
FACTOR SETTINGS FOR THE INDUCTOR DOE

Factor	Min	Max
W [um]	5	20
S [um]	2	4
N	2	4
DX [um]	25	75

Select DOE objective, design type, and model type. A DOE can be used for many purposes such as screening experiment, response surface methodology (RSM), mixture experiment, and variance component analysis. In this case, the objective is the response surface methodology, i.e., to predict the electrical responses for a given set of factor settings. To achieve the RSM objective, central composite designs (CC design), Box-Behnken design, D-optimal design are commonly used. In this example, we adopt the Box-Behnken design for the following reasons: i) the DOE space is actually bound by the factor range (unlike some CC design where the DOE space can go beyond the original factor limits), and this is important for ensuring manufacturability ii) the number of experiment runs is still reasonable for four factors (if there are more than 4 factors, the D-optimal design can be considered), iii) good rotatability compared to some CC design (e.g. central composite face-centered, CCF) and reasonable prediction quality. In order to fit a response surface, a quadratic model is chosen. If a proper transform on the response is applied, a cubic model is usually not required.

Generate worksheet and perform EM simulations for sanity check. After entering the factor settings and selecting the objective, design type, and model type in RS/1, the software will automatically generate an experiment worksheet, which lists the factor settings for each experiment run. The experiment worksheet used in our example is listed in Table II. Because a quadratic model is used, at least 3 levels are required for each factor. The minimum level is denoted by ‘-1’, the maximum by ‘1’, and the middle point by ‘0’. There are 27 runs in total. However, because 3 center points (at the bottom of Table II, run # 25, 26, and 27) are duplicates, there are only 25 different inductors. To quickly check the manufacturability and that the electrical responses from the experiment runs fall within the range of interest, EM simulations (e.g. Momentum in Agilent ADS) on the experiment runs at the selected frequency of interest can be performed. Since it is possible that the factor settings need to be modified, we have automated this checking step by a MATLAB script which launches the EM simulations according to the worksheet, extracts the electrical responses at frequency of interest, and tabulates the electrical

responses on a webpage or spreadsheet. The EM simulation results will be compared with the measured S-parameters in the next step for validating the EM simulator.

TABLE II
WORKSHEET FOR INDUCTOR DOE

Run	W	S	N	DX
1	-1	-1	0	0
2	1	-1	0	0
3	-1	1	0	0
4	1	1	0	0
5	0	0	-1	-1
6	0	0	1	-1
7	0	0	-1	1
8	0	0	1	1
9	-1	0	0	-1
10	1	0	0	-1
11	-1	0	0	1
12	1	0	0	1
13	0	-1	-1	0
14	0	1	-1	0
15	0	-1	1	0
16	0	1	1	0
17	-1	0	-1	0
18	1	0	-1	0
19	-1	0	1	0
20	1	0	1	0
21	0	-1	0	-1
22	0	1	0	-1
23	0	-1	0	1
24	0	1	0	1
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0

Build test structures and measure S-parameters for validating EM simulation results. Once we confirm the manufacturability and the response coverage, the 25 inductor test structures are built and their S-parameters are measured over the frequency of interest by a HP 8510C and a pair of 150 um pitch G-S-G probes. An ICCAP script has been developed to automate the S-parameter measurement over multiple sites and the de-embedding step. The electrical responses at the frequency of interest are then automatically extracted using a MATLAB script for comparing with the EM simulation results obtained in the previous step.

Run EM simulations over a larger DOE set and perform RSM fitting. Once the EM simulator is validated, it can be used to run a larger set of inductor DOE with 5 factors (which allows DX different from DY). The Box-Behnken design yields an experiment of 46 inductors with 6 duplicates, i.e., 41 EM simulations. The extracted electrical responses from the simulation results are then entered into

RS/1 for the RSM fitting. Most statistical software that supports RSM DOE objective has the following features: i) generate summary table of the analysis of variance (ANOVA) statistics (e.g. R^2 , R^2_{adj} values) and probability plots of the residuals and residual vs. response value plots for determining the quality of the fitting and the cause of lack of fit, ii) remove statistically insignificant terms from the model of the response by stepwise regression, iii) suggest transform on the response for the best fit, iv) adjust weightings to factors that have strong influence on the response, and v) adjust weightings to data points which are potential outliers. In this example, RS/1 suggests that a logarithmic transform on the quality factor measured at 0.9 GHz will give the best fit (see Figure 2).

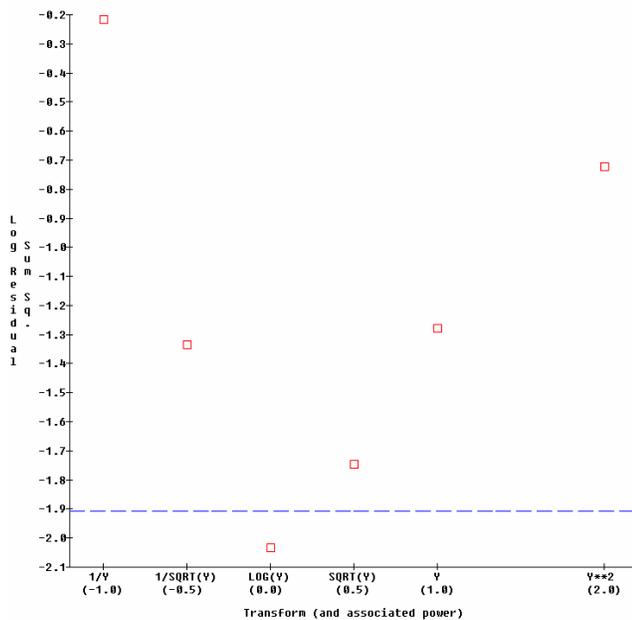


Figure 2. Sum of square of residual (in log scale) for different transforms applying to the quality factor (response) measured at 0.9 GHz. The software RS/1 suggests that a logarithmic transform will give the best fit.

Figure 3 shows the probability plot for the residual after applying the logarithmic transform on the quality factor. To improve the fitting, RS/1 suggests a bisquare regression instead of a least square method to adjust the weighting for each data point (plotted on the right hand y-axis) in order to minimize the influence of the potential outliers on both ends of the plot. After the fitting, the coefficients for the terms in the model of each response and the transformation applied to the response and the factors are provided by RS/1 (see Table III). The analytical expression for the quality factor measured at 0.9 GHz can be obtained from Table III generated by RS/1 as follows:

$$Q \text{ (at 0.9 GHz)} = \exp(1.68 + 0.40 W' - 0.0004 S' + 0.18 N' + 0.12 DX' + 0.09 DY' + 0.018 W' S' - 0.048 W' N' - 0.029 W' DX' - 0.021 W' DY' - 0.034 N' DX' + 0.019$$

$$DX' DY' - 0.208 W'^2 - 0.041 N'^2 - 0.044 DX'^2 - 0.034 DY'^2)$$

where $W' = (W-12.5)/7.5$, $S' = S-3$, $N' = N-3$, $DX' = (DX-45)/30$, $DY' = (DY-45)/30$.

Table III shows a R^2 value of 0.999 and a RMS error of 1.4% for the quality factor, indicating a good fit in this case. The same step is then repeated for other electrical responses such as the inductance, AC resistance, and the resonance frequency.

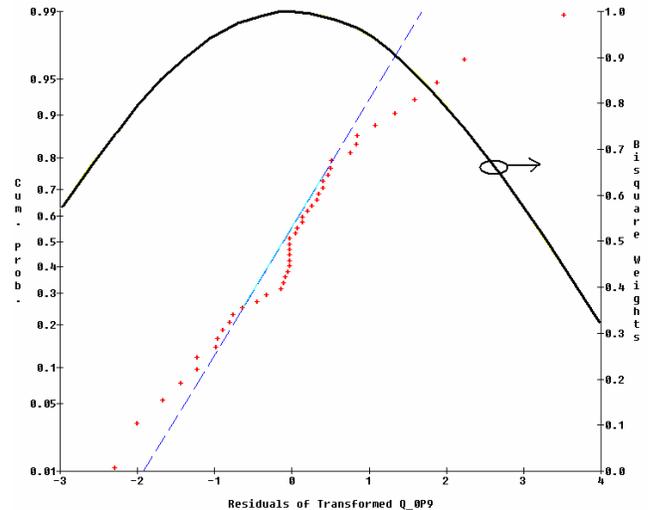


Figure 3. Cumulative probably of the residuals (left y-axis, red crosses) and the weighting (right y-axis, solid line) for bisquare regression.

TABLE III
COEFFICIENTS AND SCALING FACTORS FOR THE QUADRATIC MODEL AND FITTING ERROR OF THE QUALITY FACTOR AT 0.9 GHz.

Term	Coeff.	Std. Error	T-value	Signif.
1	1.683110	0.004460		
2 ~W	0.397610	0.003423		
3 ~S	-0.000411	0.003423		
4 ~N	0.177532	0.003423		
5 ~DX	0.116167	0.003423		
6 ~DY	0.089778	0.003423		
7 ~W*S	0.017811	0.006847		
8 ~W*N	-0.048398	0.006847	-7.07	0.0001
9 ~W*DX	-0.029301	0.006847	-4.28	0.0002
10 ~W*DY	-0.020571	0.006847	-3.00	0.0053
11 ~N*DX	-0.033510	0.006847	-4.89	0.0001
12 ~DX*DY	0.018584	0.006847	2.71	0.0109
13 ~W**2	-0.207707	0.004460	-46.58	0.0001
14 ~N**2	-0.040809	0.004460	-9.15	0.0001
15 ~DX**2	-0.044494	0.004460	-9.98	0.0001
16 ~DY**2	-0.034334	0.004460	-7.70	0.0001

No. cases = 46 R-sq. = 0.9985 RMS Error = 0.01369
Resid. df = 30 R-sq-adj. = 0.9978 Cond. No. = 4.362
~ indicates factors are transformed.

IMPLEMENTATION OF INDUCTOR TOOL IN CIRCUIT SIMULATOR

The analytical expressions obtained from the RSM fitting can be implemented as an inductor tool in the circuit simulator. In this paper, we implement the tool in Agilent

ADS. The graphical user interface (GUI) is created using TCL/Tk script. The inductor tool is integrated into ADS via the Inter-Process Communication (IPC). This tool has two modes of operation. In the ‘calculator’ mode (see Figure 4(a)), the designer inputs the geometrical dimensions of the inductor and the tool will output the electrical properties at the selected frequency of interest.

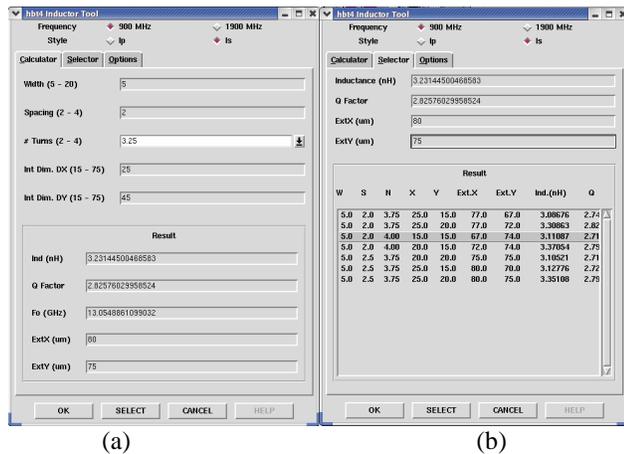


Figure 4. Inductor tool implemented in Agilent ADS circuit simulator: (a) calculator mode, (b) selector mode.

In the ‘selector’ mode (see Figure 4(b)), the tool gives a list of potential inductors which satisfy the electrical properties and layout area requirement specified by the designer. The designer can click on one of the inductors on the list and hit the ‘Select’ button to place the inductor instance on the schematic for full S-parameter simulation over the whole frequency range at a later design phase.

FURTHER VALIDATION

Inaccuracies from this tool mainly come from i) the EM simulations (which have been validated with the measurement of the first set of DOE composed of 25 square-shaped inductor test structures) and ii) the RSM fitting of the electrical responses extracted from the simulation results for the larger set of DOE composed of 41 rectangular-shaped inductors (which has also been quantified by RS/1). For the purpose of developing the inductor tool, this two-step validation is sufficient. But for the sake of showing the feasibility of the development flow of this tool, we have fabricated and measured the larger DOE set of 41 rectangular-shaped inductors and compared measured electrical properties with those predicted by the tool. In addition, we built 24 inductor test structures with geometrical parameters in between the DOE points (see Figure 5) to further check the predictability of the tool. Table IV summarizes the comparison results and shows that the tool has reasonably good accuracy in the property prediction at both the DOE points and the in-between points.

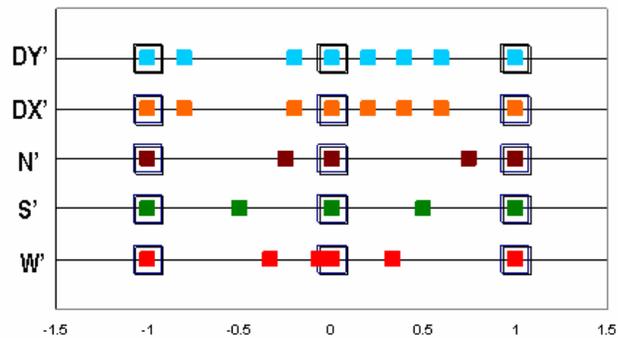


Figure 5. Normalized geometrical parameters of inductor test structures measured for tool validation.

TABLE IV
ROOT MEAN SQUARE ERROR IN PREDICTED INDUCTOR ELECTRICAL PROPERTIES WITH RESPECT TO MEASUREMENT

	RMS % error at 41 DOE points	RMS % error at 24 in-between points
L, 0.9 GHz	5.7	7.1
Q, 0.9 GHz	12.8	10.9
L, 1.9 GHz	9	8
Q, 1.9 GHz	5.8	7.6
Resonance freq.	3.0	4.6

CONCLUSIONS

We have demonstrated that by using a DOE approach and EM simulations we only need to measure a relatively small set of inductor test structures for developing an inductor tool which predicts reasonably well the electrical properties of the rectangular-shaped inductors on Skyworks’ InGaP HBT process. The tool is accurate enough in an early design phase since the inductor can behave differently once it is placed in the actual circuit environment. The implementation of this tool in Agilent ADS circuit simulator for design automation has been discussed.

ACKNOWLEDGEMENT

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REFERENCE

[1] L. F. Tiemeijer et. al., IEEE Trans. MTT, 2006, 54(8), pp.3378-3386.

ACRONYMS

- ADS: Advanced Design System
- DOE: Design of Experiment
- EM: Electromagnetic
- HBT: Heterojunction Bipolar Transistor
- InGaP: Indium Gallium Phosphide
- RSM: Response Surface Methodology