On-chip Inductor Modeling in Digital CMOS technology and Dual Band RF Receiver Design using Modeled Inductor

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Abstract: The main research on this paper is to model on-chip inductor in digital CMOS technology by using the foundry parameters and the physical structure. The s-parameters of a spiral inductor are extracted from the modeled equivalent circuit and then compared to the results obtained from HFSS. The structure and material of the inductor used for modeling in this work is identical with those of the inductor fabricated by CMOS process. To show why the modeled inductor instead of ideal inductor should be used to design a RF system, we designed dual band RF front-end receiver and then compared the results between when using the ideal inductor and using the modeled inductor.

Index Terms – Digital CMOS, Spiral Inductor, Equivalent model, Foundry parameters, HFSS, S-parameter, Radio Frequency, Dual-Band Receiver

1. INTRODUCTION

In a rapidly increasing mobile market, each functional block has been integrated as SOC (system on a chip). According to trend, many people are interested in RFIC (radio frequency integrated circuit) using silicon CMOS technology. IC must be designed by digital CMOS technology to realize SOC because digital block is much larger than analog block in an IC chip. Thus, digital CMOS technologies have been researched. However, it is hard to predict the performance of the designed chip in spite of many efforts, which results from inaccuracy in RF models.

The general method how to design IC in digital CMOS is to make and then measure a test pattern of active and passive components. If the measured performance for the designed circuit is not identical with the predictions, the circuit should be modified and measured once again, and whenever the problem occurs, the above procedure will be repeated. This methodology is cost- and time- consuming. So, the accurate model of components enables to lessen the above complexities. The conventional works do give information about the active device modeling, however, not about the inductor modeling on CMOS foundry [6],[11]. The focus on this paper is to model the inductor, not active devices. Since the model parameters of CMOS is presented by CMOS fabrication company (Hynix Inc.) and it is assumed that those parameters are very accurate, modeling active devices can be omitted.

In the section 2, inductance, capacitance, and resistance of a spiral inductor with a geometric structure based on the foundry parameters are calculated by analytic equations and then the ADS equivalent circuit is made [3],[7].

In the section 3, the s-parameter obtained from the equivalent circuit in section 2 is compared with that from 3-D EM field simulator (HFSS) for verification of the accuracy of the modeled equivalent circuit.

In the section 4, why the accurate model of inductor should be used to design RF system is shown by comparing the performance when we using the modeled inductor and ideal inductor. The dual-band RF front-end receiver at 2.45 and 5.25 GHz is designed by using the modeled inductor. The used process is Hynix 0.25 μm digital CMOS technology.

2. SPIRAL INDCUTOR

2.1. Overview of Spiral Inductor

Spiral inductor, which is one of the most important passive devices for RF circuit design consists of metal lines. According to inductance of the circuit, number of metal line of inductor is various. Each metal line is connected by via hole in CMOS technology. Fig 1 shows square structure of used spiral inductor. Characteristic of spiral inductor is determined by metal length, metal width, spacing between metal line and number of turns. Variation of each parameter changes inductance and Q (quality) factor of inductor. Equivalent model of spiral inductor, which we used, is shown in Fig 2. It is made up of passive components. Passive components consist of C_s (series capacitance), L_s (series inductance), R_s (series resistance), C_{ox} (oxide capacitance), C_{si} (silicon substrate capacitance) and R_{si} (silicon substrate resistance). Equivalent model was made by geometric structure of spiral inductor.

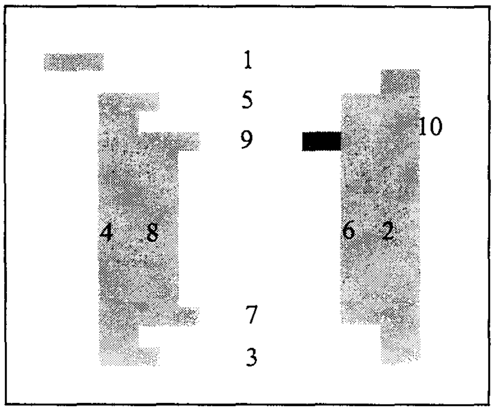
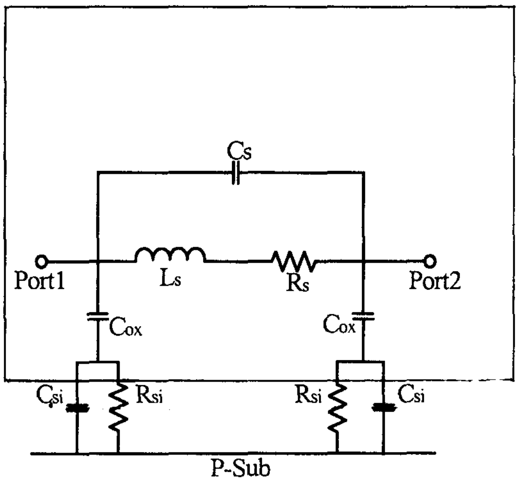


Fig. 1. Geometric structure of spiral inductor



2.2. Calculation of Equivalent Model

There are many modeling methods of spiral inductor such as Greenhouse method, Bryan method, Terman method, and etc. In this paper, we used Greenhouse method for an accurate calculation [1].

Inductance and Q factor are very important to inductor. Although inductances of inductors are same, Q factor is changed by numerical value of layout parameters of inductor, such as metal length, metal width, line spacing and number of turns. Because Q factor depends on coupling effect, eddy current, substrate loss, feed-through capacitance, and self-resonance at high frequency. Those are optimized that used inductor can get high quality factor at 5.2 GHz in this paper [2]-[4]. And then, we get layout parameters, such as metal length = 220 μm, metal width = 8 μm, line spacing = 3 μm and number of turns = 2.25. Geometric structure of used inductor is shown in Fig 1. Spiral inductor can be divided into segments. Series inductance, which is the most important factor in the spiral inductor, is equal to the sum of inductance of divided segments. Because spiral inductors have a squire structure, all segments of used spiral inductor have a direction, and those have a mutual inductance. Thus, we calculated series inductance (L_s) by the sum inductance of segments and mutual inductance from equation (1) to equation (6).

$$L_s = L_{segment} + M_T \qquad (1)$$

$$M_T = \sum M_{plus} - \sum M_{minus} \qquad (2)$$

$$L_{segment} = 2l\{\ln[\frac{2l}{w+t}] + 0.50049 + [\frac{w+t}{3l}]\} \qquad (3)$$

Mutual inductance has adding section and subtracting section according to direction. For example, 1th and 5th segments (M_{15}), which are the same direction, have a plus value. 1th and 3th segments (M_{13}), which are the opposite direction, have a minus value. Mutual inductance of used inductor has plus components of six and minus components of ten. Mutual inductance can calculate as

$$M = 2lQ \qquad (4)$$

$$Q = \ln\{(\frac{l}{GMD}) + [1 + (\frac{l^2}{GMD^2})]^{\frac{1}{2}}\} - [1 + (\frac{GMD^2}{l^2})]^{\frac{1}{2}} + (\frac{GMD}{l}) \qquad (5)$$

$$\ln GMD = \ln d - \{[\frac{1}{12}(\frac{w}{d})^2] + [\frac{1}{60}(\frac{w}{d})^4] + [\frac{1}{168}(\frac{w}{d})^6] + [\frac{1}{360}(\frac{w}{d})^8] + \ldots\} \qquad (6)$$

where

L_s Series inductance in nH;
$L_{segment}$ Segment inductance in nH;
M_T Total mutual inductance in nH;
l Length of segment in cm;
w Width of segment in cm;
t Thickness of segment in cm;
d Distance between segments in cm;
Q Mutual inductance parameter;
GMD Geometric Mean Distance between segments.

According to structure of inductor, parasitic components of used inductor can be calculated by foundry parameters; dielectric constant, sheet resistance, thickness and etc. Calculated series inductance and equation of parasitic components of used inductor are summarized in Table 1 [1],[5],[6].

Table 1. Parasitic component and calculated value

Equation	Value
L_s : Greenhouse	2.6254 nH
$R_s = \frac{\rho l}{\omega\delta(1-e^{-t/\delta})}$	3.954 Ohm
$C_s = n\omega^2 \frac{\varepsilon_{ox}}{t_{oxM5-M4}}$	5.5224 fF

$C_{ox} = \frac{1}{2} l\omega \frac{\varepsilon_{ox}}{t_{ox}}$	43.94 fF
$C_{si} = \frac{1}{2} l\omega C_{sub}$	12.38 fF
$R_{si} = \frac{2}{l\omega G_{sub}}$	3.23K Ohm

3. SIMULATION COMPARISION

Equivalent model of inductor, which was made the same structure of inductor, which will be manufactured, was calculated by foundry parameters. In the same way, inductor model of HFSS (High Frequency Structure Simulator) was made [8]. Layout structure of inductor in 3D EM simulator is shown in Fig 3.

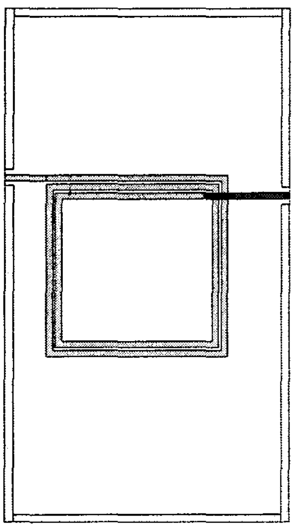


Fig 3. Layout structure of 3D field simulator

The 3D model has a ground both side of inductor and a fifty-Ohm termination in both ports with CPW (coplanar wave guide) structure. That model was simulated until 10 GHz, twice of utilization frequency. We compared S-parameter of equivalent model with that of 3D model. Compared results are shown in Fig 4 and Fig 5.

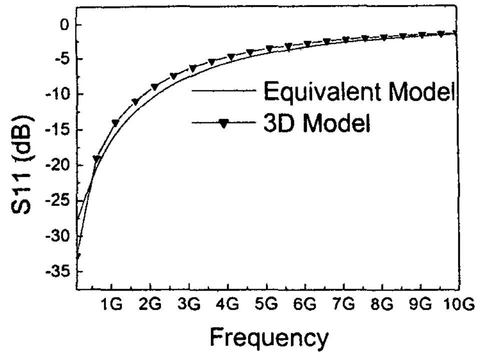


Fig 4. dB(S(1,1)) of equivalent model and 3D model

In Fig 4, we know return loss is almost accurate until 10 GHz. Moreover, S (2,1) curve of equivalent model and 3D model is a comparative sameness in Fig 5, which was shown both magnitude and phase characteristic.

In Fig 5, the shape of SRF (self resonance frequency) is not shown until 10 GHz, because series capacitance is small in operation frequency. In fact we can see SRF at 35 GHz when we swept frequency from 100 MHz to 40 GHz.

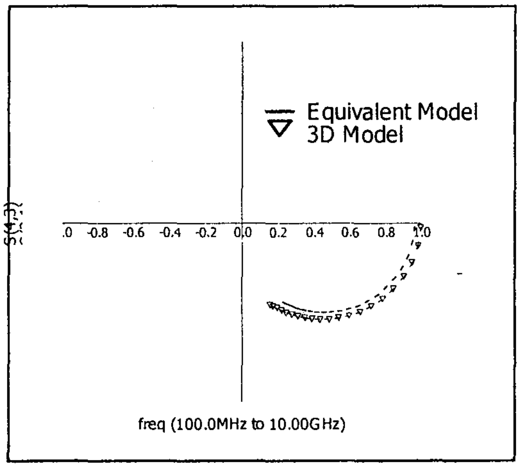


Fig 5. Polar(S(2,1)) of equivalent model and 3D model

We know that a made equivalent model is relatively accurate below 10 GHz when we compared equivalent model with 3D model in Fig 4 and 5. Because it is well known to us that 3D model accurate relatively. As simulation results, inductor, which will be manufactured, can be replaced by equivalent model.

4. RF RECEIVER DESIGN

4.1. Necessity of equivalent model

When some circuits were designed in digital CMOS technology, if those were designed without verified high-frequency model, results of those would be different from expected results. Fig 6 shows RF front-end receiver for wireless LAN (local area network).

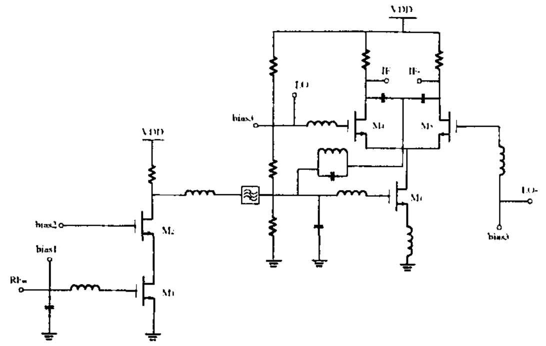


Fig 6. RF front-end receiver for wireless LAN

We expect that if designed receiver didn't use a RF model, the result is very different. Thus, we compared the circuit using by ideal elements with that using by equivalent model. Compared results are shown in Fig 7 and Fig 8.

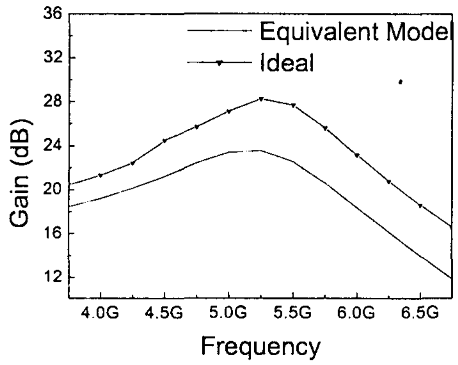


Fig 7. Gain plot of equivalent model and ideal element

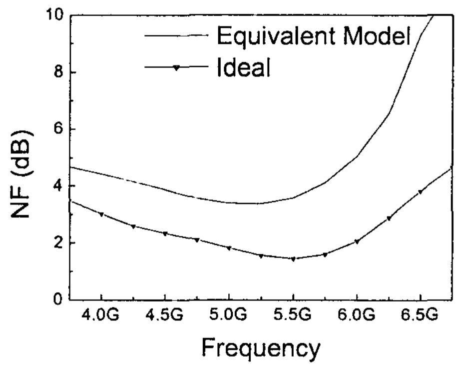


Fig 8. NF plot of equivalent model and ideal element

Difference of equivalent model and ideal element is gain of 5 dB and NF (noise figure) of 2 dB at the frequency of 5.25 GHz. In a system, it is a great problem that difference of gain is a 5 dB, because efficiency of the system can be changed. Most of all, difference of NF is enormous. In a front-end receiver, NF is the most important factor. And the first amplifier is remarkably affected with NF in the RF receiver.

Therefore, in the result of Fig 8, difference of 2 dB is the same that characteristic of the first amplifier was changed. The LNA (low noise amplifier), the first amplifier, is not accordance with amplifier, which will be manufactured. Accordingly, we must need either RF model or S-parameter of manufactured components when we design RF circuits in digital CMOS.

4.2. Dual band RF front-end receiver design

In this paper, we designed dual band RF receiver with extracted S-parameter of inductor.

Application of designed receiver is Bluetooth of 2.45 GHz ISM (industrial, scientific and medical) band and wireless LAN of 5.25 GHz 802.11a band. The 802.11a standard has two frequency bands at 5 GHz range, 5.18 ~ 5.32 GHz and 5.745 ~ 5.8 GHz. Used frequency band of 802.11a is 5.18 ~ 5.32 GHz. In the circuit, all of the inductors are replaced with S-parameter of equivalent model of inductor.

In a CMOS technology, we use a feedback structure for stability because silicon technology has low stability and substrate loss.

In the circuit of Bluetooth, LNA was made with a single transistor. LNA used a feedback resister for stability and has an optimized matching circuit for low NF. Mixer was composed of a DBM (double balanced mixer) structure of Gilbert cell [9]. It has high conversion gain and isolation characteristic. In the circuit of wireless LAN, LNA was composed of cascade structure for high gain and stability. Mixer was composed of a SBM (single balanced mixer) structure. It has a feedback circuit for high linearity. And for excluding isolation and feed-through of LO and IF signal, we used a filter in the feedback circuit [10]. Design results of dual band RF front-end receiver are shown in Table 2.

Table 2. Simulation results of dual band RF receiver

	2.45 GHz	5.25 GHz
Supply voltage (V)	2.5	2.5
Overall Gain (dB)	23	23.5
Overall NF (dB)	2.8	3.36
Return loss (dB)	-26	-17
OIP3 (dBm)	18 (*LNA*) 8 (*Mixer*)	12 (*LNA*) 6 (*Mixer*)

Although we use a digital CMOS technology, which has not a RF model, we expect we will get a relatively good result. Design method by S-parameter of inductor, which will be manufactured, will be accurate. Fig 9 shows layout of dual band RF front-end receiver.

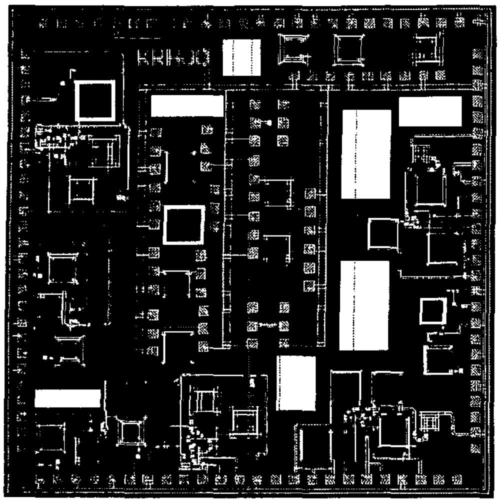


Fig 9. Layout of dual-band RF front-end receiver

5. CONCLUSION

Digital CMOS technology is hard to make not only an on-chip inductor but also a RF model. Thus, it is difficult to design RF circuits in digital CMOS technology, and those are not accurate.

In this paper, we explained a relatively accurate design method without manufacture process of several times. As a used method, if we use a S-parameter of equivalent model, which is the same inductor with foundry parameters, we can get accurate results of manufactured chip. This methodology will help the RF SOC design in digital CMOS technology.

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