Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 446-447

P2-18L

Monolithic Transformer Modeling Based on the 4-port Characterization Technique

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1. Introduction

On-chip transformers have been found to have several functions in RF applications, such as impedance matching, impedance conversion, signal coupling and phase splitting. Among the various kinds of transformers, inter-wound transformers comprising two independent and identical spirals, have advantages of less area and higher quality factor in differential mode RFIC's applications [1].

Although compact models for on-chip transformers have been established in some literatures [1-3], the parameter extraction methods used there were based on EM simulators, such as FastHenry, or derived approximate analytic expressions, such as those reported in Ref. [4]. These methods need some process parameters and must obey some prerequisites to accurately extract the model parameters, so it's not a feasible way for some applications.

Oppositely, in this paper, a 4-port transformer model with its parameter extraction method based on one 4-port S-parameter measurement has been presented for the first time. With the magnetically de-coupling method presented here, the traditional modeling technique used for the on-chip spiral inductor can be invoked to simplify the modeling task. Verification with measurd data demonstrates the feasibility of the proposed transformer model.

2. Experiments

The equivalent-circuit of the monolithic transformer used in this paper is shown in Fig. 1. It is a combination of two identical 9-element spiral inductor model plus inter-coupling components, such as magnetic coupling coefficient K, and coupling capacitances, C_{pp} and C_m.

The port definition and the photograph for the inter-wound transformer used in this paper are shown in Fig. 2. The transformer consists of two identical spirals, and the metal trace width, the space between two neighbored traces, the inner diameter and the turn number for each spiral are 10um, 2um, 146um, and 3.25, respectively. It was fabricated in the 0.18um 6-metal CMOS process. The 4-port S-parameter measurement was performed by ATN-4000 multi-port test system and the measurement frequency range is between 50MHz and 6GHz. After de-embedding the corresponding OPEN dummy device by Y-parameter subtraction method used in [3], the de-embedded 4-port S-parameter matrix (S_i) can be obtained.

3. Parameter extraction and modeling results

To de-couple the two windings for extracting the model parameters for the spiral inductor, the de-embedded 4-port S-parameter must be transformed to 2-port S-parameter for one winding by leaving two terminals of the other winding open. It can be easily conducted by lots of circuit design tools, such as Agilent ADS. Due to one winding left open, the mutual inductance between the two windings can be ignored. Meanwhile, if we assume that the coupling capacitances between them are small enough to be neglected, this 2-port S-parameter would represent the electrical behavior of the winding which can be modeled by the spiral inductor model depicted in Fig. 3.

The conventional extraction method presented in [5] may be exploited to extract the parameters of the spiral inductor. However, some modification must be made to let it work since the measurement frequency is not high enough to obtain the so-called resonant frequency that, in turn, is used to extract the related parameters. The modified procedure used here is described in the following paragraph.

First, the model shown in Fig. 3 is divided into three parts labeled as **A**, **B**, **C**. Here we make a assumption that part **A** is equal to part **C** for this PI structure. The admittance of parts **A** and **B** can be obtained from the matrix manipulation (namely, $Y_{o,A}$ and $Y_{o,B}$ where the subscript 'o' stands for the condition where one winding opened). C_{ox}, R_{sub}, L_s and R_s can then be directly extracted from $Y_{o,A}$ and $Y_{o,B}$ at the lowest frequency. After these extraction steps, C_{sub} can be obtained from local optimizations for $Y_{o,B}$.

Then, these model parameters extracted in the above procedure can be put into the complete 4-port transformer model shown in Fig. 1. L_s and R_s are divided into 2 parts to take the mid-winding coupling effect into account. The capacitances in this model can be viewed as open-circuits at low frequencies,. In this condition, the equivalent circuit for the 4-port transformer would be simplified as that shown in Fig. 4, and it is obvious that the coupling coefficient, K, can be obtained from the following expression:

$$K = -1 \Big/ real\left(\frac{Y_{i,11}}{Y_{i,31}}\right) \qquad (1)$$

, where Y_i 's are transformed directly form S_i's.

Finally, the values of the port-to-port and mid-winding coupling capacitances C_p, C_{pp} and $C_{m,}$ are obtained from the optimization results of the 4 by 4 S-parameter matrix S_i. Table 1 summarizes the extracted model parameters of the monolithic inter-wound transformer. Figures 5 and 6 show the simulation results of the proposed transformer model where only 4 of 16 S-parameters are shown due to the symmetry. The simulation result obviously agrees with the measured data and verifies the validity of the presented model along with its parameter extraction method.

4. Conclusions

In this paper, we establish a lumped-element model for monolithic transformer based on well-known 9-element model of the spiral inductor. For the first time, the model parameters can be extracted directly from only one 4-port S-parameter measurement. Owing to the split of the spiral inductor from the complete 4-port model, the modeling task can be achieved as those used for the traditional 9-element model of the spiral inductor plus additional optimizations for coupling capacitances between two windings. The modeling results of proposed simple extracting technique shows its validity is up to 6GHz.

Although the inter-wound transformer is chosen in the study because its model parameters are more easily to be extracted due to its symmetric structure. We can apply the magnetically de-coupling method to other kinds of transformer models. That means, with some modifications based on different physical structure of the monolithic transformers, the modeling procedure presented here can still work well for other kinds of transformers.

References

[1] J. J. Zhou, and D. J. Allstot, "Monolithic transformers and their application in a differential CMOS RF low-noise amplifier," *IEEE J. Solid-State Circuits*, vol.33, pp.2020-2027, Dec 1998

[2] S. S. Mohan et al., "Modeling and characterization of on-chip transformers," *IEEE IEDM Tech. Dig.*, pp.531-534, Dec 1998

[3] T. Kamgaing et al., "Performance analysis of monolithic RF transformers by experimental characterization," *IEEE MTT-S Dig.*, pp. 205-208, Jun. 2002

[4] H. Hasegawa, M. Furukawa, and H. Tanai, "*Properties of microstrip line on Si-SiO2 system*," IEEE trans. Microwave Theory Tech., vol. MTT-19, pp. 869-881, Nov. 1971

[5] C. Y. Su et al., "A macro model of silicon spiral inductor," *Solid-State Electronics*, vol. 46, pp. 759-767, May 2002

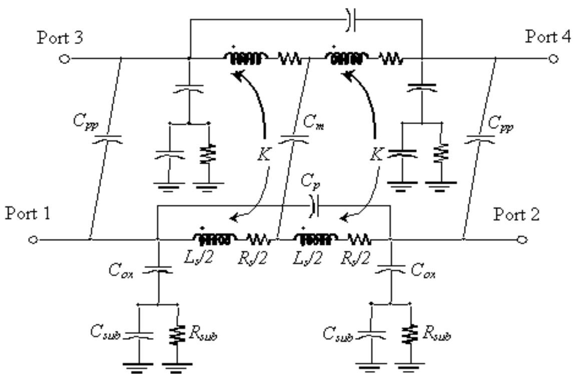


Fig. 1 4-port equivalent-circuits of the monolithic transformer model. Note the model parameters for the second winding are neglected for simplification and clarification.

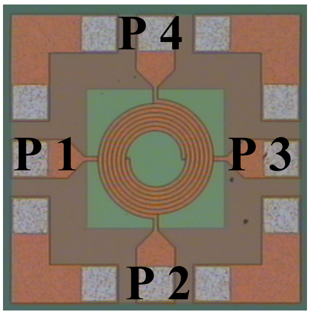


Fig. 2 Photograph and the port definition of the monolithic

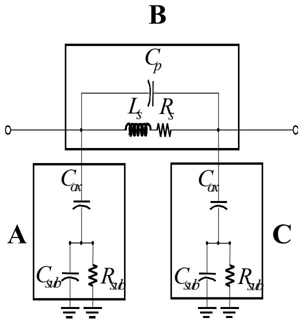


Fig. 3 Conventional 9-element equivalent-circuits model of the spiral inductor

Table 1 Extracted model parameters of the inter-wound transformer

L_s(H)	R_s(Ω)	C_{ox}(F)	R_{sub}(Ω)	C_p(F)	C_{sub}(F)	K	C_m(F)	C_{pp}(F)
3.5n	4.3	81f	693	18f	51f	0.74	278f	26f

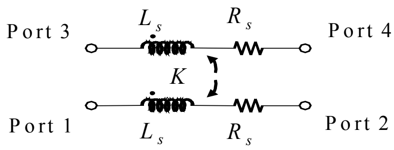
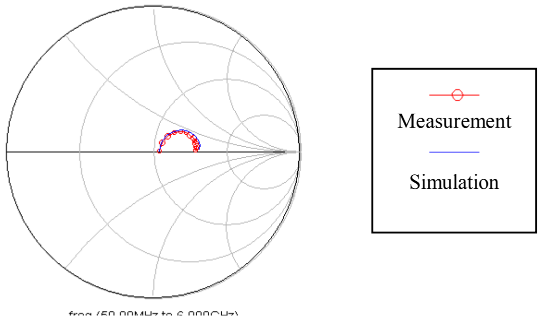


Fig. 4 Equivalent circuit of the 4-port transformer at low frequencies



Fi[...]ed $S_{i,11}$ traces of the

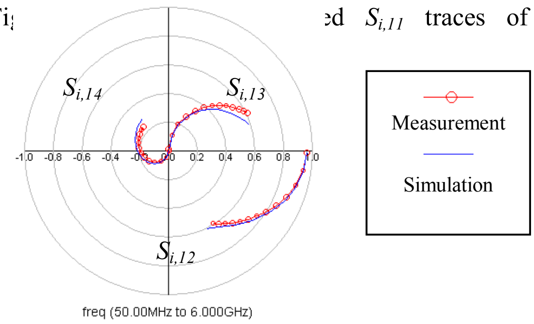


Fig. 6 Measured and simulated $S_{i,12}$, $S_{i,13}$, and $S_{i,14}$ traces of the monolithic transformer