A simple method of measuring differentially-excited on-wafer spiral inductor-like components

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Abstract: This paper proposes a simple method of measuring differentially-excited on-wafer RF CMOS spiral inductor-like components. This method requires only two common 'G-S-G' probes and an ordinary two-port VNA. Using a network instead of a detailed equivalent circuit, this method completes the de-embedding with only one 'Through' dummy, and thus the measurements are greatly simplified. By designing the ports 'Open' or 'Short-circuited' deliberately, a multi-port transformer can be transformed into three two-port networks with different terminators. Then, couplings between the two coils can be solved, and the differentially-excited scattering parameters (S-parameters) can be constructed. Also, a group of differential inductors and transformers were designed and measured, and then comparisons between simulated and measured electromagnetic results are performed to verify this method.

Key words: on-wafer; differentially-excited; de-embedding; two-port network; S-parameter

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1. Introduction

With the development of radio-frequency integrated circuits (RFICs), CMOS spiral inductor-like components are becoming more attractive. For inductors, they are widely used in LC-tanks or matching networks. For transformers, some are used for matching or isolating adjacent stages[1, 2], and some are used to substitute inductors for quality-factor consideration[3–5]. In RFICs, differential circuits are so popular that modeling of differentially-excited components becomes necessary. As a result, techniques of differential measurements have become more important.

Many papers have studied different ways to measure differential inductors[6, 7]. In these references, 'Open' and 'Short' dummies are usually required for de-embedding, and thus large wafer areas are wasted. So, it is necessary to establish a simpler measuring method with reduced dummies. Compared to inductors, transformers are more complicated due to more ports. Generally speaking, we can measure differentially-excited transformers by three means: (1) Use a 4-port VNA with the differential measurement capability. In this way, a pair of complicated 'G-S-G-S-G' probes is required, and thus the calibration and de-embedding will be exhausting. (2) Use a 2-port VNA and a pair of on-wafer wideband baluns. However, how to design such on-wafer wideband baluns is a big problem. (3) Use a 2-port VNA with perfect terminators. The VNA measures 2 ports at a time while the remaining ports are terminated by a system impedance. Repeat this process several times with different combinations of ports, and then the differentially-excited S-parameters can be constructed from the measured data. However, perfect terminators are nearly impossible for on-wafer wideband measurements. To solve this, rigorous methods of measuring with imperfect terminators were first proposed in Refs. [8, 9], and later two methods that reduce the measurement time and repeatability difficulty were further proposed in Ref. [10]. In addition, by using a 2-port VNA, Zoltan[11] proposed a method of measuring 3-port differential inductors with the unmeasured port being floating, which is too complicated for the modeling of numerous components, and Iosu[12] proposed a method of measuring transformers with 'G-S-G' and 'S-G-S' probes, which is also complicated with limited accuracy.

In this paper, a new method of measuring differentially-excited inductor-like components with an ordinary 2-port VNA is proposed. It requires only two 'G-S-G' probes and one 'Through' dummy, and thus the probe calibration and the de-embedding are greatly simplified. Finally, this method is verified by comparisons between measured and EM-simulated results.

2. De-embedding process

A group of octagonal differential inductors and an octagonal transformer were fabricated in SMIC 0.18-μm RF CMOS technology, as listed in Table 1. The six differential inductors' metal width and spacing are 10 μm and 2 μm respectively, but they were designed in different styles purposely. For example, R60T3_65 means its inner radius ($R_{\rm in}$) and turns are 60 μm and 3 respectively, and suffix '_65' means its winding is composed of metal layer 6 parallel with metal layer 5. Besides the induc-

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Table 1. Test structures.

Structure		Description
Differential inductor	R40T3	R_{in} = 40 μm, Turns = 3, Metal layer 6
	R40T4	R_{in} = 40 μm, Turns = 4, Metal layer 6
	R40T5	R_{in} = 40 μm, Turns = 5, Metal layer 6
	R60T3_6	R_{in} = 60 μm, Turns=3, Metal layer 6
	R60T3_65	R_{in} = 60 μm, Turns=3, Metal layer 6//5
	R60T3_654	R_{in} = 60 μm, Turns = 3, Metal layer 6//5//4
Transformer	P1P2O	Port-1 and Port-2 are open
	P3P4O	Port-3 and Port-4 are open
	P3P4S	Port-3 and Port-4 are short-circuited
Dummy	TH	'Through' for de-embedding

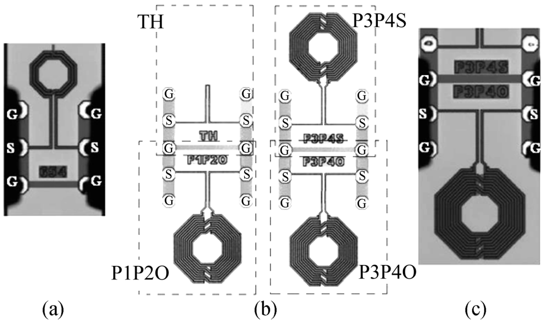


Fig. 1. (a) Die photo of R60T3_654; (b) Test structures of a transformer; (c) Die photo of P3P4O.

tors, P1P2O, P3P4O, and P3P4S are test structures for measuring a 5:5-turn two-coil spiral transformer, in which Port-1 and Port-2 belong to the primary coil and Port-3 and Port-4 belong to the secondary coil. The transformer's inner radius, metal width, and spacing are 80 μm, 10 μm, and 1.5 μm, respectively. TH is the only dummy structure for de-embedding. For all these structures, only two 'G-S-G' probes are used during the on-wafer measurement, as shown in Fig. 1.

With the increase of frequency, parasitic effects of pads and conductive conductors become more and more important, and thus the de-embedding becomes more and more complicated. In the standard 'Short-Load-Open-Through (SLOT)' method, for a device-under-test (DUT), at least two dummies are needed to de-embed parallel and series parasitics. To reduce the complexity, a de-embedding method using only one 'through' dummy was originally proposed in Ref. [13]. It uses a 2-port network instead of a detailed equivalent circuit to describe the pads and connective conductors. To make the most use of the same dummy, we proposed a new 'Through' dummy structure, as shown in Fig. 2, which can be viewed as two back-to-back equal halves due to its symmetric layout. Because each half branch is a passive reciprocal network, its single-ended 2-port S-parameters can be calculated as below:

$$S_{p\_11} = S_{p\_22} = \frac{S_{th\_11} + S_{th\_22}}{2 + S_{th\_12} + S_{th\_21}}, \quad (1)$$

$$S_{p\_12} = S_{p\_21} = \sqrt{0.5\,(S_{th\_12} + S_{th\_21})\left(1 - S_{p\_11}^2\right)}. \quad (2)$$

Network parameters S_{th}, S_{raw}, and S_p represent the 'Through' dummy, the testing structure with pads, and the

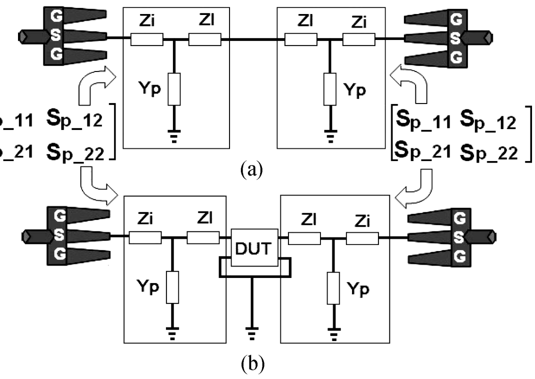


Fig. 2. Test structures: (a) The 'Through' dummy; (b) DUT with the pads.

dummy's half branch, respectively. Though the dummy's half branch is not perfectly symmetric, the assumption that $S_{p\_11} = S_{p\_22}$ is proved practicable and reliable in this work. After solving S_p, we transform S_{raw} and S_p to T_{raw} and T_p separately, and then the DUT's intrinsic T-parameters can be calculated by

$$T_{dut} = T_p^{-1} T_{raw} T_p^{-1}.$$

Then, the de-embedding is completed after we transform T_{dut} to S_{dut}. After that, the reference planes are moved to the ports of the DUT exactly.

3. Construction of differentially-excited *S*-parameters

3.1. Differential inductors

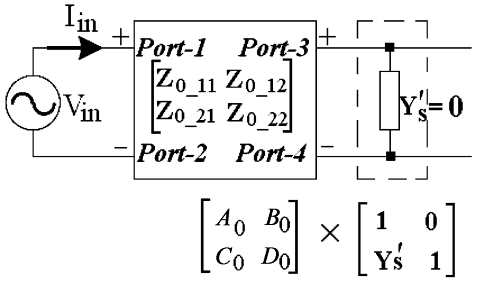
During the de-embedding process, all S-parameters are based on single-ended 2-port networks, and then we can transform them to differentially-excited 1-port Z-parameters as mentioned in Refs. [6, 7].

$$S_{diff\_dut} = (S_{dut\_11} + S_{dut\_22} - S_{dut\_12} - S_{dut\_21})/2, \quad (4)$$

$$Z_{diff\_dut} = 100(1 + S_{diff\_dut})/(1 - S_{diff\_dut}). \quad (5)$$

After that, the system impedance is changed from 50 to 100 Ω accordingly. For differential inductors, their inductances and quality factor can be solved as below:

$$L_{diff\_dut} = \mathrm{Imag}(Z_{diff\_dut})/(2\pi f), \quad (6)$$


(a)

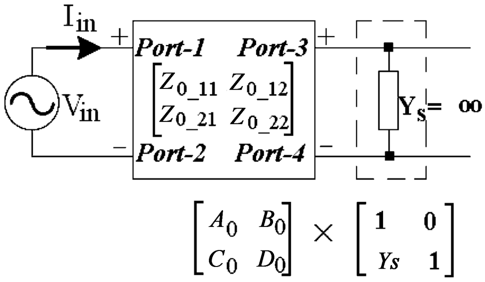

(b)

Fig. 3. Definition of Z_{11} in differentially-excited modes of (a) P3P4O and (b) P3P4S.

$$Q_{\text{diff\_dut}} = \text{Imag}(Z_{\text{diff\_dut}})/\text{Real}(Z_{\text{diff\_dut}}). \quad (7)$$

3.2. Differentially-excited transformer

For the measured transformer, additional steps should be taken based on Z-parameters $Z_{\text{diff\_P3P4O}}$, $Z_{\text{diff\_P3P4S}}$, and $Z_{\text{diff\_P1P2O}}$. For example, $Z_{\text{diff\_P3P4O}}$ is the differential input impedance between Port-1 and Port-2 while Port-3 and Port-4 are open, and Z_0 is the transformer's intrinsic differentially-excited 2-port Z-parameters. According to the definition of Z_{11}, we have

$$Z_{0\_11} = Z_{\text{diff\_P3P4O}}. \quad (8)$$

Similarly, we have

$$Z_{0\_22} = Z_{\text{diff\_P1P2O}}. \quad (9)$$

Because the transformer is a passive reciprocal network, the opposing off-diagonal elements of its impedance matrix Z_0 are equal, and we can obtain

$$Z_{0\_12} = Z_{0\_21}. \quad (10)$$

As shown in Fig. 3, the terminator at unmeasured ports is a 2-port network, which is cascaded with the transformer. In P3P4S, Port-3 and Port-4 are short-circuited by a short metal conductor. In P3P4O, Port-3 and Port-4 are open. Thus, admittance Y'_S is infinitesimal while admittance Y_S is infinite. Then, we can calculate the ABCD matrix of P3P4S as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{P3P4S}} = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y_S & 1 \end{bmatrix} = \begin{bmatrix} A_0 + B_0 Y_S & B_0 \\ C_0 + D_0 Y_S & D_0 \end{bmatrix}. \quad (11)$$

According to basic knowledge on 2-port networks, we can obtain

$$Z_{\text{diff\_P3P4S}} = \lim_{Y_S \to \infty} \frac{A_0 + B_0 Y_S}{C_0 + D_0 Y_S} = \frac{B_0}{D_0} = \frac{(Z_{0\_11} Z_{0\_22} - Z_{0\_12} Z_{0\_21})/Z_{0\_21}}{Z_{0\_22}/Z_{0\_21}} = Z_{0\_11} - Z_{0\_12} Z_{0\_21}/Z_{0\_22}. \quad (12)$$

Then, we can calculate Z_{0_12} as below:

$$Z_{0\_12} = Z_{0\_21} = \sqrt{Z_{\text{diff\_P1P2O}}(Z_{\text{diff\_P3P4O}} - Z_{\text{diff\_P3P4S}})}. \quad (13)$$

Finally, we can solve the transformer's differentially-excited 2-port S-parameters from Z_0.

4. Experimental results

The on-wafer measurement was performed on a S300 probe station. Before the measurement, a full 2-port calibration was conducted to make sure the measured data were reliable. After this, the calibration reference planes were moved to the points of probes exactly. In this work, Agilent's ICCAP was used for the measurement and data processing.

4.1. Measured results of differential inductors

To verify our method, we simulated the inductors with an electromagnetic (EM) simulator (ADS Momentum), and set up the substrate conditions based on SMIC technology strictly. Figures 4 and 5 show the differential inductances when the turns and the parallel metal layers are changed respectively, as well as errors between measured and EM-simulated inductances. Though the measurements are performed carefully, measured errors, such as variations of contact resistances, are still introduced into the measured data. Measured errors are so small that their effects will decrease with inductances. In other words, measured and EM-simulated inductances become more well matched when the turns are increased, as shown in Fig. 4. Generally speaking, for RFIC designers, an inductor is often used as an inductive component when the working frequency is below half of its self-resonant frequency (SRF). As a result, only errors between measured and EM-simulated inductances at low frequencies are useful for modeling. From Figs. 4 and 5, it is clearly that the maximum error inductance in the applicable frequency range is much less than 3%, which is accurate enough for modeling. In addition, SRF itself instead of inductances at SRF has a greater impact on modeling. Among the six inductors, the largest error between measured SRF and EM-simulated SRF is much less than 4%, which hardly affects the model accuracy. In conclusion, this method works well in measuring differential inductors.

4.2. Measured results of the differential-excited transformer

According to Eqs. (1)–(13), the differentially-excited S-parameters can be solved. However, some attention should be paid to the data processing. When ICCAP solves the square

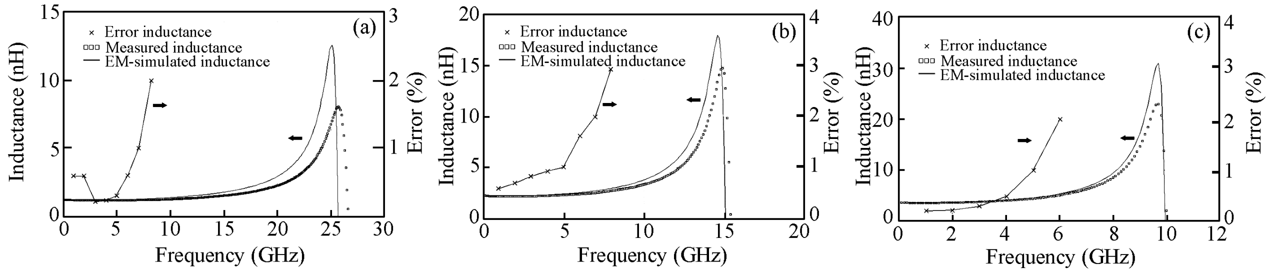


Fig. 4. Comparison between measured and EM-simulated inductances: (a) R40T3; (b) R40T4; (c) R40T5.

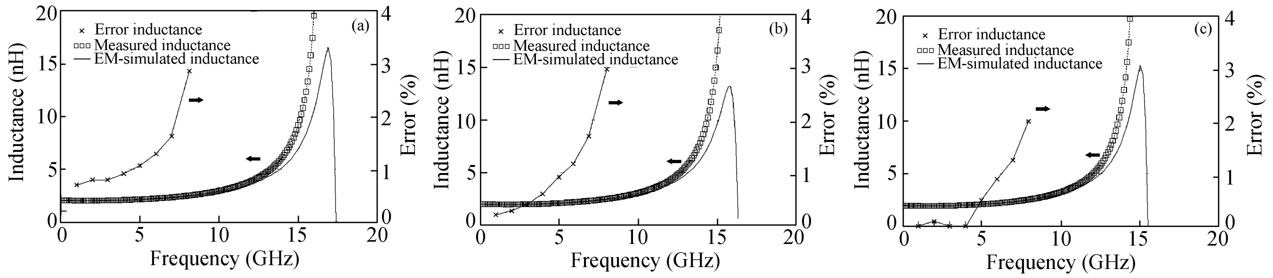


Fig. 5. Comparison between measured and EM-simulated inductances: (a) R60T3_6; (b) R60T3_65; (c) R60T3_654.

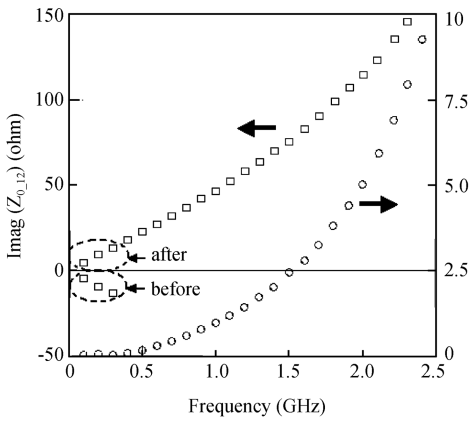


Fig. 6. Calculated coupling impedance Z_{0_12} before and after the data correction.

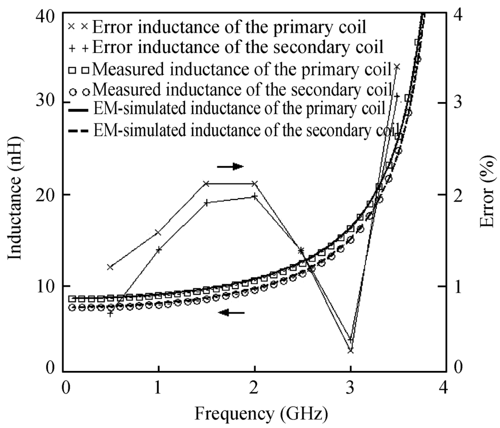


Fig. 7. Comparison between measured and EM-simulated coil inductances.

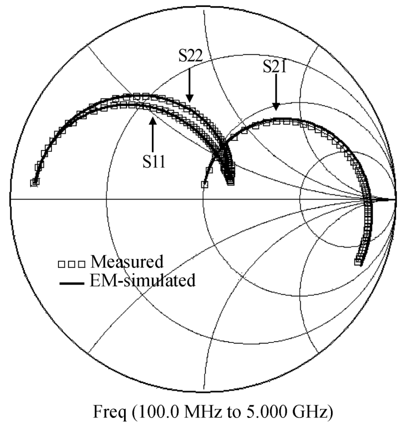


Fig. 8. Comparison between measured and EM-simulated S-parameters.

root of a complex number, it may get a conjugate answer that unfortunately has an incorrect physics meaning. To take an example, below the coil's self-resonant frequency, Z_{0_12} should be inductive; however, its calculated value from ICCAP is capacitive. As shown in Fig. 6, all calculated values are correct except the first three values below 0.4 GHz. In fact, these three error values come from ICCAP's inner arithmetic instead of Eq. (13) itself. As a result, we solve this problem by correcting them to their conjugate values accordingly. After that, the curves become smoother and more reliable.

Similarly, we simulated the transformer with Momentum carefully. Below the coil' SRF ($\approx$ 4 GHz), errors between measured and EM-simulated coil inductances are less than 3.5%, as shown in Fig. 7, and measured S-parameters are perfectly consistent with EM-simulated S-parameters, as shown in Fig. 8. Because measured results and EM-simulated results come from two totally different approaches, such a tiny difference between them is convincing enough to prove our method. In conclusion, this method also works well in measuring differential transformers.

5. Conclusions

This paper proposes a simple method of measuring differentially-excited on-wafer spiral inductor-like components. In this method, only two 'G-S-G' probes and an ordinary 2-port VNA are required. Instead of 'open' and 'short' dummies, only one 'Through' dummy is used to totally de-embed all the parasitic effects. Six differential inductors and a transformer are both adopted in this method and EM-simulators respectively. The differences between the measured and EM-simulated results are so small that this method is validated correspondingly.

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