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Differential Measurement and Parameter Extraction of Symmetrical Inductors

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Abstract

Measurements and extraction of Q-value and self-resonance frequency of on-chip differential symmetrical inductors have been performed. Both 1-port and 2-port measurements have been carried out. In the 1-port measurements a high frequency broadband 180° hybrid was used to generate differential signals. The inductor was then excited by the same kind of signals in the measurement as when used in a real differential circuit. The measurement results agree well with simulations using FastHenry in combination with the free inductor optimization program Indentro, verifying these tools.

1 Introduction

Symmetrical inductors are essential in RFICs, which typically use differential topologies to improve the performance by suppressing even order non-linearities and substrate interference. Differential inductors are common in e.g. differential oscillators [1] and low noise amplifiers [2].

Modern RF CMOS processes have high silicon substrate resistivity as well as thick top metal options, significantly increasing the performance of monolithic inductors. To design first time right and thereby reducing the design costs, accurate inductor models are needed for simulations. Earlier work has therefore developed such models based on 2-port measurements, for both single ended inductors [3] [4] [5] [6] and differential ones [7] [8].

2 Indentro

The inductor optimization program Indentro [9] is used for comparison to our measurements. Its theory of equivalent distributed capacitances [1] is in this paper verified with measured on-chip inductors. Indentro uses simple lumped II-models to optimize the geometry of spiral and symmetrical inductors. The models are depicted in Fig. 1.

Thanks to the simplicity of the algorithm, and using fast empirical and semi-empirical formulas to calculate the lumped II-model, Indentro reduces the optimization time greatly compared to field solvers. When a suitable geometry has been found using the fast formulas, an accurate II-model is created using FastHenry for the inductive and resistive parts, and the equivalent distributed capacitances from Indentro. This final equivalent lumped II-model is valid for a single frequency only, and when sweeping the frequency a new II-model is therefore calculated for each frequency.

2.1 Equivalent Distributed Capacitances

As can be seen in Fig. 1(a) a differentially excited symmetrical inductor has an equivalent distributed capacitance between the two outer terminals of \( C_{sym:tt} \approx C_{ox:tt} L / 2 \) and terminal to ground \( C_{sym:tg} \approx C_{ox:tg} L / 6 \), where \( L \) is the total length of the inductor. For spiral inductors, excited single-endedly, \( C_{spit:tt} \approx C_{ox:tt} L / n^2 \), where \( n \) is the number of turns, and \( C_{spit:tg} \approx C_{ox:tg} L / 3 \). The capacitances \( C_{ox:tt} \) and \( C_{ox:tg} \) are given in \((F/m)\) and are calculated with concise expressions using microstrip theory, whereas the corresponding division factors are eval-
2.2 C_{ox:tt} For Naked versus Molded Die

It is assumed that the isolation material on top of the metal has infinite thickness. This is a fairly good assumption if the die is placed in a molded plastic package. However, with the die naked as in the case of probing this is not true, since the passivation material is usually less than 1 \mu m thick. The capacitance, C_{ox:tt}, thus changes significantly. A change of C_{ox:tt} is particularly hazardous for symmetrical inductors. The influence of this capacitance is large due to the low division factor of 2, compared to spiral inductors which have a factor close to the number of turns squared, n^2, see Fig. 1. As can be seen in Fig. 2, for a very thin passivation layer, and h_{package} = 0, the field lines C_{gdt} travel mostly through air with \epsilon_{air} = 1 rather than SiO_2 dielectric with \epsilon_r \approx 4.

We now evaluate the difference in C_{ox:tt} between a naked die and a molded one. The total capacitance between the strips are:

\[ C_{ox:tt} = \frac{C_{gdt} + C_{gt} + C_{gdb}}{2} \]  (1)

Unless the strips are thick and narrow, and has a small spacing, C_{gdt} and C_{gdb} dominate over C_{gt}. Thus for strip lines with a thin passivation layer, and under the assumption that C_{gdt} \approx C_{gdb}, we get:

\[ C_{ox:tt} \approx C_{gdt:mold} \frac{\epsilon_{air}}{\epsilon_r} + C_{gdb} \approx C_{gdt:mold} \left( 1 + \frac{\epsilon_{air}}{\epsilon_r} \right) \]  (2)

Compared to C_{ox:tt} \approx 2C_{gdt:mold} the capacitance C_{ox:tt} decreases by a factor of (3) for a naked die compared to a molded package that Indentro assumes.

\[ C_{sym:tt:die} = \frac{C_{sym:tt}}{2} \approx C_{sym:tt} \frac{1}{1.6} \]  (3)

The change of value of C_{sym:tt:die} will be used later on when comparing the results of Indentro and Fast-Henry to the measurements. The change is less for inductors with thick metal and small spacing, when C_{gt} has more influence.

The short circuit structures were simulated with Fast-Henry. The two structures are plotted in Fig. 5, where the darker wires are in thick top metal layer, used for power grids and high quality inductors, and the lighter are in metal 1. The series inductance and resistance for the differential 1-port signals is simulated with a through from port to port, and for the 2-port as a short between signal and ground at the end of the wires.

The simulated impedance of the feeding paths is subtracted from Z_{ind'} [11] [10], and Z_{ind} is finally calculated as:

\[ Z_{ind} = Z_{ind'} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot Z_{oh} \]  (5)
4 Measurements and Results

Three symmetrical inductors on four different chips have been measured. Two chips were measured with a 1-port method, and the other two with a 2-port. A die photo of two of the inductors can be seen in Fig. 6, and their geometries are presented in Table 1.

The inductors are not optimized for high Q-value, but in order to verify the results of Indentro they have rather been chosen with different parameter settings in terms of radius, width, spacing, and number of turns.

A 0.18μm CMOS process with 6 metal layers and high substrate resistivity (10Ω-cm) was used, including a thick top metal option for inductors and power lines. The 2μm thick top metal of aluminum is located approximately 5μm above the metal 1 shield of the test inductors.

The measurements have been conducted with a HP8720C Vector Network Analyzer (VNA), which measures from 50 MHz-20 GHz. Infinity probes from Cascade Microtech1 was used. The probe measurements seemed to be sensitive to skating distances, and efforts were therefore made to maintain an equal skating length of 25μm for reproducibility of the results.

The VNA and probes were calibrated with an Impedance Standard Substrate (ISS), which provides open, short, load, and through structures. WinCal from Cascade Microtech was used to calibrate the VNA and collect the data. The de-embedding of the measured data followed the procedure in Section 3, with an open pad structure on-chip and simulated short structures with Fast-Henry (one for 1-port and another for 2-port).

4.1 1-port Measurement

The measured and corrected curves were limited to the balun’s frequency range, 2 GHz-18 GHz. To get the best differential signal from the balun three different cables was tested on different outputs of the balun, thus a total of six combinations were tested. The 1-port measurements were compensated for the error in phase and magnitude of the 180° hybrid before extracting the differential Q-value.

4.2 Results

The differential Q-value and self-resonance frequency, \( f_r \), were extracted from the three inductors described in Table 1 and the results are plotted in Fig. 7. The Q-value was calculated by:

\[
Q = \frac{\Im[G(Y_{in})]}{\Re[G(Y_{in})]} \tag{6}
\]

where we have used \( Y_{in} = Y_{11} \) for 1-port measurements, and \( Y_{in} = Y_{11} - Y_{12} \) for 2-port. The self-resonance frequency can be found as the frequency where Q equals zero (13 GHz for inductor II). As can be seen, the 1-port and 2-port measurements are in alignment with the simulation results by Indentro and FastHenry. Since the die

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1The probes are in a GSG configuration with a pitch of 100 μm. The frequency range is from DC to 40 GHz. The contact resistance is less than 50 mΩ on aluminum pads.
is naked and not molded the capacitance $C_{\text{sym:lt}}$, calculated by Indentro, has been compensated with (3) for a better agreement in terms of $Q$-value and self-resonance frequency.

5 Conclusion

Measurements of inductors on a lightly doped CMOS substrate have been carried out with 1-port and 2-port techniques. $Q$-value and $f_{sr}$ have been compared with Indentro, a free inductor design tool, and the agreement is good up to $f_{sr}/2$.

References


Figure 7. Comparison between Indentro with FastHenry, and 1-port and 2-port measurements.