High Frequency Measurement Techniques for On-Chip Inductors

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Abstract:
This paper presents high frequency measurement techniques of on-chip inductors in giga Hertz range for wireless communication products. The on-chip inductors were fabricated on high resistive substrate to reduce loss. We compared several different on-chip inductors for self-resonance frequency and quality factors. The collection of measurement data could be used for the guideline of designing practical spiral inductors for wireless applications.

Keywords: Inductors, quality factor, s-parameter

I. INTRODUCTION

There is a high demand for small footprint, high performance, low power and low cost wireless products in today's mobile communication market. In order to meet these demands, many off-chip passive devices are being moved to on-chip as integrated passives as in Package in Package (PIP), SIP or SOP forms, Inductors are very important passive elements in many circuit applications such as frequency synthesizers, narrow-band impedance matching, low noise degeneration and feedback, linear filters and baluns [1, 2]. There are many papers written in design and fabrication of integrated inductors for wireless applications [3-6]. However, the inductors fabricated on a lossy silicon substrate provide low Q that makes the performance of high bandwidth wireless systems decrease in performance. This paper presents measurement techniques of on-chip inductors in Giga Hertz range for wireless communication products. We compared several different on-chip inductors for self-resonance frequency and quality factors. The measurement data could be used for the guideline of designing practical spiral inductors for wireless applications. We present characterization and testing of integral passives that are fabricated on a very high-resistivity silicon substrate. We provide modeling of the spiral inductor and compare the results with the extracted values to optimize the model. We measured several kinds of inductors, which have one or two ports, with or without ground shields. The measurement shows that one-port inductors with ground shields have a higher quality factor than those without ground shields. The self-resonance frequency decreases quickly as the number of turns of the inductor increase. We made a setup of optimizing procedure for the equivalent circuit parameters of spiral inductors from the measured scattering parameters.

II. MEASUREMENT

A. Quality factor and self-resonance frequency

We measured several on-chip spiral inductors on a very high resistivity substrate with HP8510 network analyzer and Cascade probe station. The measurement system was calibrated with LRRM technique. The scattering parameters were then converted to admittance parameters as Eq. (1) [7],

$$[Y] = [Y_0]([1]-[S])([1]+[S])^{-1} \quad (1)$$

Where, $[Y_0] = \begin{bmatrix} Y_0 & 0 \\ 0 & Y_0 \end{bmatrix}$

The parasitics of the inductor pads were de-embedded using open structure on the same substrate. The admittance parameters of the inductor itself were obtained by subtracting out the open structure admittance parameters from the spiral inductor admittance parameters. The quality factor of the measured inductors was calculated as traditional method [8].

$$Q = -\frac{\mathrm{Im}(y_{11})}{\mathrm{Re}(y_{11})} \quad (2)$$

We then plotted the quality factors as the function of frequency. The maximum quality factor was found on the plot. The self-resonance frequency was determined by the quality factor at the point where Q is zero.

B. Extraction of the equivalent circuit parameters

The equivalent circuit of two-port spiral inductor is shown Fig. 1 [8]. The series branch consists of the serial inductance L_S, the serial resistance R_S, and the series feed forward capacitor C_S. Two parallel branches represent parasitics of port-1 and port-2. The capacitor C_{OX} represents the capacitance between the spiral and the substrate. The silicon substrate is modeled by C_{SUB} and R_{SUB}.

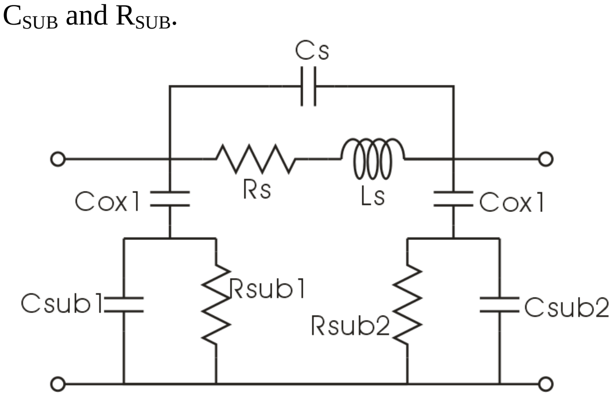


Fig. 1 Equivalent circuit of two-port spiral inductor.

We used optimization technique to find the equivalent circuit parameters. It is not easy to optimize the nine unknown circuit parameters from scratch. So we simplified the two-port equivalent circuit as π-circuit shown in Fig. 2. Then the branch admittances were calculated from the admittances of the inductor in simple π-circuit as

$$Y_1 = y_{11} + y_{12} \quad (3.a)$$

$$Y_2 = y_{22} + y_{12} \quad (3.b)$$

$$Y_3 = -y_{12} \quad (3.c)$$

The series branch Y_3 includes the R_S, L_S, and C_S. The shunt branch Y_1 and Y_2 include the C_{OX}, C_{SUB}, and R_{SUB}. We could then optimize the three unknowns instead of nine unknowns. We used commercial software (Agilent ADS) for optimizing three unknowns. The initial values are important in optimization technique. We used the simplified equivalent circuit as shown in Fig. 3. The values of C_S, C_{SUB1}, and C_{SUB2} are very small. The initial values can be calculated in case of simplified circuit as

$$R_S = \mathrm{Re}\left(-\frac{1}{y_{12}}\right) \quad (4.a)$$

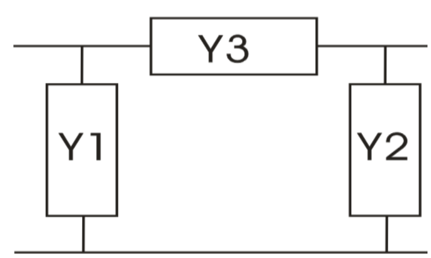
$$L_S = \frac{1}{\omega}\mathrm{Im}\left(-\frac{1}{y_{12}}\right) \quad (4.b)$$

$$R_{SUB1} = \mathrm{Re}\left(\frac{1}{y_{11}+y_{12}}\right) \quad (4.c)$$

$$C_{OX1} = -\frac{1}{\omega}\frac{1}{\mathrm{Im}\left(\frac{1}{y_{11}+y_{12}}\right)} \quad (4.d)$$

$$R_{SUB2} = \mathrm{Re}\left(\frac{1}{y_{22}+y_{21}}\right) \quad (4.e)$$

$$C_{OX1} = -\frac{1}{\omega}\frac{1}{\mathrm{Im}\left(\frac{1}{y_{22}+y_{21}}\right)}$$



(4.f)

Fig. 2 Simplified π-circuit for two-port spiral inductor.

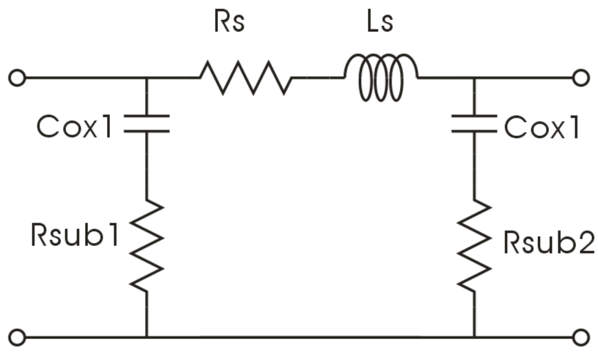


Fig. 3 Simplified equivalent circuit of two-port spiral inductor.

III. RESULTS

Several kinds of spiral inductors were measured. The measured inductors have one or two ports, with or without ground shields. As shown Fig. 4, spiral inductors have a different number of turns (N), metal width (W), space (S) between the spiral metals, inner diameter (D) of the spiral, and connection line length (L) between the pad and the inductor. We used inductors that are normal and shorter line length between the pad and the inductor with two ports. We also used inductors that are unshielded and shielded inductors with one-port.

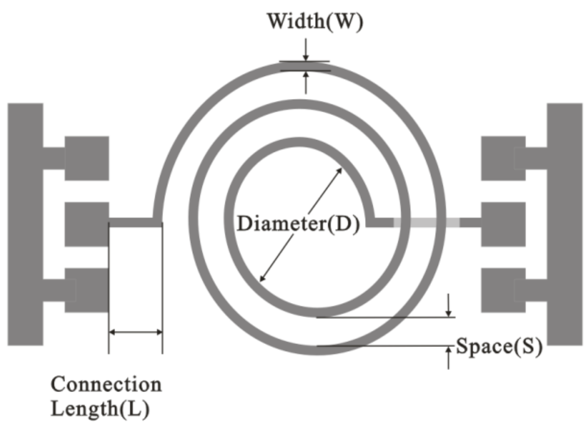


Fig. 4 The sketch of circular spiral inductor with 2.5 turns.

Figure 5 shows s-parameters for simulated and measured on-chip inductor. As shown in the figure, the two results are very close which indicates good extraction values. The simulation was performed on ADS.

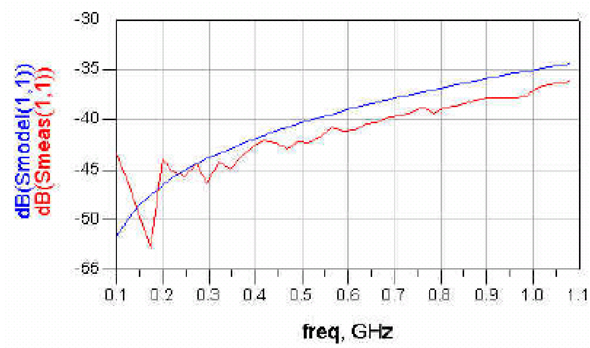


Fig. 5. S-paramerter of measured and simulated inductor.

We have fabricated variety of on-chip spiral inductors on high resistive silicon substrate to minimize loss. Figure 6 illustrates some of the on-chip inductors that were fabricated. The shapes of these inductors vary from circular to rectangular and inner diameters of the inductors changed from 2mm to 8mm.

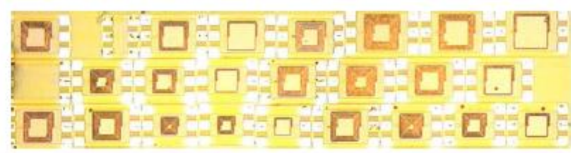


Fig. 6. Varieties of on-chip inductors.

Figure 7 provides a simple measurement setup for high frequency measurements.

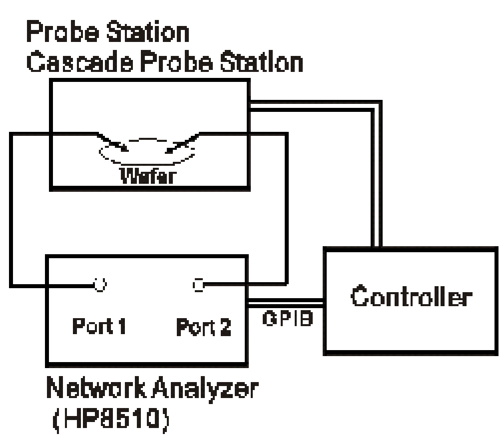


Fig. 7. Measurement Set-up.

The set up consisted of Cascade microprobe station and HP8510 40GHz network analyzer. Figure 8 and 9 provide measured Q factors using HP8510. The measured Q factors were 4 and 14 for the maximum Q values at 7 GHz.

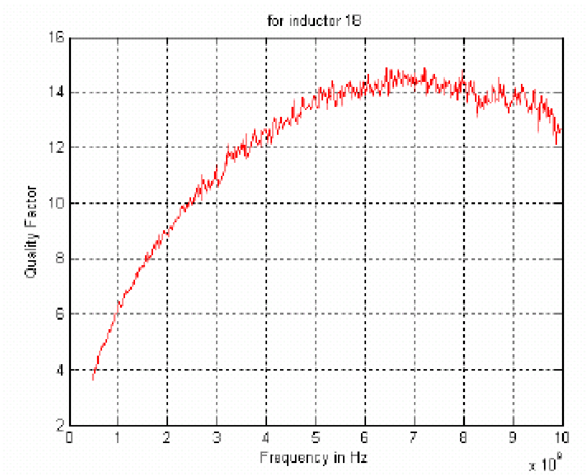


Fig. 8. Measured Q value from an inductor.

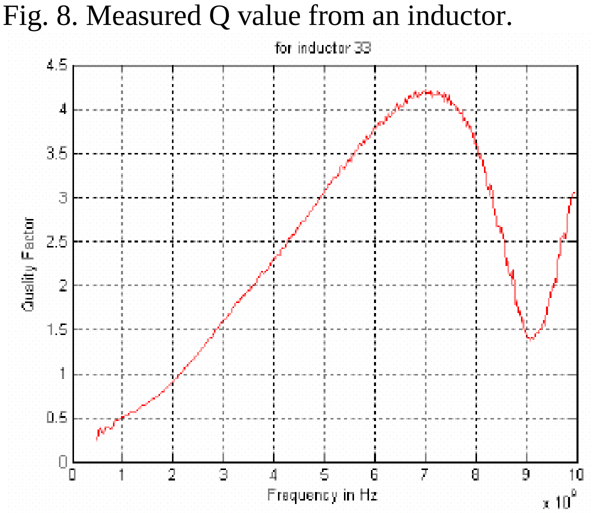


Fig. 9. Measured Q value from an inductor.

Figure 10 shows a typical inductor that was fabricated on a high resistive silicon substrate. The inductors had different inner diameters and turns ratios.

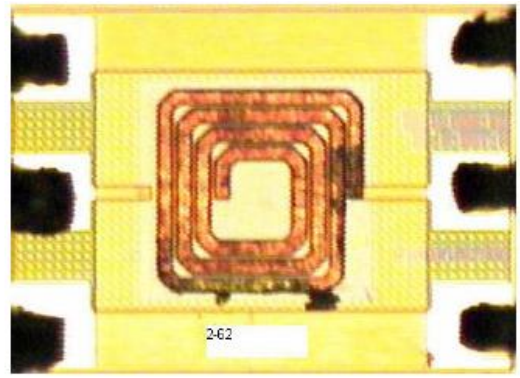


Fig. 10. Example of fabricated on-chip inductor.

We extracted the circuit parameters of the spiral inductors. The extracted parameters of a spiral inductor are shown in Table 1. We verified this method by generating scattering parameters from known circuit elements and then comparing values of circuit elements with the optimization results of ADS scattering parameters.

Table. 1 Extracted parameters of the equivalent circuit of a two-port spiral inductor.

Circuit parameter	Extracted value
L_S	6.66 nH
R_S	2.82 Ω
C_P	0.216 pF
C_{OX1}	0.597 pF
R_{SUB1}	61.2 kΩ
C_{SUB1}	0.130 pF
C_{OX2}	0.592 pF
R_{SUB2}	99.9 kΩ
C_{SUB2}	0.106 pF

The quality factors with varying inner diameter of the spiral inductor are measured. The inner diameter of the spiral inductors has little influence on the maximum quality factor. The measured self-resonance frequency with varying number of turns is shown in Fig. 11. Two-port inductors have lower self- resonant frequency than one-port inductors as shown in the bars (a) and (c) of Fig. 11. The self- resonance frequency decreases as the number of spiral turns increases. Because when the number of spiral turns increases, the parasitic capacitance increases with it. Therefore, the self-resonance frequency becomes lower.

The self-resonance frequency has little relationship with the space as shown in data bars (a) and (e) of Fig. 11. In Fig. 12, the self-resonant frequency decreases as the inner diameter of spiral increases.

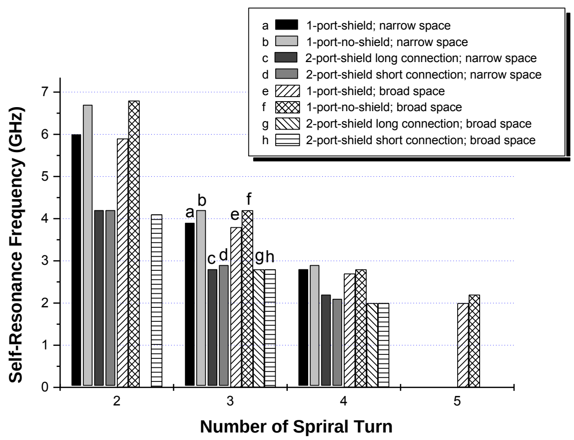


Fig. 11 Self-resonance frequency as varying the number of spiral turn, space between the metal lines, number of ports, and length between pad and inductor.

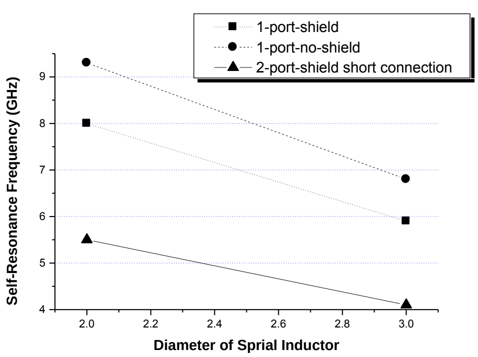


Fig. 12 Self-resonance frequency as varying the inner diameter of the spiral inductors for wide space.

IV. CONCLUSION

This paper presented measurements of on-chip inductors that were fabricated on high resistive silicon substrate. We measured several types of inductors, which have one or two ports, with or without ground shields. The measurement shows that one-port inductors with ground shields have a higher quality factor than those without ground shields. The self-resonance frequency decreases quickly as the number of turns of the inductor increase. We provided optimization procedures for equivalent circuit parameters of all physical shaped inductors on a substrate. We verified this method of measurement using s-parameters from a network analyzer.

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