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An Analysis of Layout and Temperature Effects on Magnetic-Coupling Factor, Resistive-Coupling Factor, and Power Gain Performances of RF Transformers for RFIC Applications

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Abstract - In this paper, we demonstrate a comprehensive analysis of the temperature effect (–25 ^{o}C ~ 175^{o}C) on the quality-factors (Q_1 and Q_2), magnetic-coupling factor (K_{Im}), resistive-coupling factor (K_{Re}), maximum available power gain (G_{Amax}), and minimum noise figure (NF_{min}) performances of RF bifilar and stacked transformers for RFIC applications. Excellent G_{Amax} of 0.713 and 0.806 (i.e. NF_{min} of 1.469 dB and 0.937 dB) were achieved at 5 GHz and 7 GHz, respectively, at room temperature (RT), for a 1:1 stacked transformer mainly due to its high K_{Im} and K_{Re}. In addition, for the 1:1 bifilar transformer at RT, though its K_{Im} and K_{Re} are low, good G_{Amax} of 0.636 and 0.631 (i.e. NF_{min} of 1.965 dB and 2.0 dB) were still achieved at 5 GHz and 7 GHz, respectively, mainly due to its high Q_1 and Q_2.

I. Introduction

In the design of ultra-low-voltage high-performance transformer-feedback VCOs [1] and LNAs [2], the power gain G_A (or noise figure NF) performance of the transformers used are crucial for the phase noise performance of the VCOs and the NF performance of the LNAs. However, the G_A (or NF) performance of monolithic RF transformers fabricated on normal silicon substrates are not satisfactory up to now mainly due to the K_{IM}, the K_{Re}, and the quality-factors (of the primary and the secondary coil) which are not high enough [3]. Various methods have been proposed to improve the Q-factors of RF passive devices, such as high-resistivity silicon, front-side and backside micromachining, porous silicon, proton implantation, and substrate transfer [3]. However, no detailed analyses of the layout and the temperature effects on the K_{Im} and K_{Re} performances of various important RF transformers have been reported. Therefore, in this work, we demonstrate an analysis of the temperature effect (–25 ^{o}C ~ 175^{o}C) on the quality-factors (Q_1 and Q_2), K_{Im}, K_{Re}, G_{Amax}, and NF_{min} performances of RF bifilar and stacked transformers for RFIC applications.

II. Transformer Structure

The transformers under study were fabricated with a 0.18 μm RF CMOS technology on a p-type silicon substrate (resistivity : 10 Ω-cm) with thickness of 700 μm. The main features of the backend processes are as follows. There are 6 metal layers, named M1 to M6 from the bottom to the top. The thickness of M6 is 0.99 μm, and that of M1-M5 is 0.53 μm. Fig. 1 shows the 3D schematic diagrams of the 1:1 bifilar transformer (transformer-A), and the 1:1 stacked transformer (transformer-B). Table I is a summary of the primary layout parameters and the extracted small-signal equivalent circuit parameters of transformers A-E.

III. Measurement Results and Discussions

The frequency-dependent S-parameter measurements were performed from 0.1 GHz to 20 GHz by an HP-8510C network analyzer. Fig. 2(a) shows the measured equivalent Q-factors of the primary coil (Q_1) and the secondary coil (Q_2) of transformer-A and transformer-B. Good Q_1 of 8.8 and 9.4, Q_2 of 7.5 and 7.1 were achieved at 5 GHz and 7 GHz, respectively, for transformer-A. This is better than that (i.e. Q_1 of 5.8 and 1.6, Q_2 of 3.6 and 1.6 at 5 GHz and 7 GHz, respectively) of the transformer-B. The higher Q_1 and Q_2, and the larger self-resonance frequency of the primary coil (f_{SR1}) and the secondary coil (f_{SR2}) of transformer-A are attributed to its lower series metal resistances R_{s1} and R_{s2}, and lower parasitic (or overlap) capacitance C_p between the primary coil and the secondary coil (see Table I). Fig. 2(b) shows the measured K_{IM} and K_{Re} of transformer-A and transformer-B. As can be seen, high K_{Im} of 1.083 and 1.009, K_{Re} of 0.487 and 0.977 were achieved at 5 GHz and 7 GHz, respectively, for transformer-B. This is better than that (i.e. K_{Im} of 0.536 and 0.522, K_{Re} of 0.111 and 0.15 at 5 GHz and 7 GHz, respectively) of transformer-A. The higher K_{Im} and K_{Re} of transformer-B is attributed to its smaller equivalent vertical distance (VD) [4].

Fig. 3(a) shows the measured Q_1 and Q_2 of transformer-A at various temperatures. As can be seen, the measured Q_1 and Q_2 decrease with the increase of temperature mainly due to the positive temperature coefficient of the series metal resistance R_{s1} and R_{s2}. The measured temperature dependence of $R_{1\text{-}eff}$ at low frequencies (i.e. R_{s1}) is linear. The corresponding temperature coefficient is $3.94\times10^{-3}/^{o}$C at 0.1 GHz, which is very close to the result ($3.9\times10^{-3}/^{o}$C) reported in the literature. Fig. 3(b) shows the measured K_{IM} and K_{Re} of transformer-A at various temperatures. As can be seen, the temperature dependences of both K_{IM} and K_{Re} are very weak. Fig. 6(c) shows the measured G_{Amax} both before and after the test pads were de-embedded of transformer-A at various temperatures. Fig. 7(a) shows the measured Q_1 and Q_2 of transformer-B at various temperatures. Fig. 7(b) shows the measured K_{IM} and K_{Re} of transformer-B at various temperatures. Fig. 7(c) shows the measured G_{Amax} of transformer-B at various temperatures both before and after the test pads were de-embedded. The same trends as those of transformer-A were observed.

IV. Conclusions

The present analysis is helpful for RF engineers to design temperature-insensitive ultra-low-voltage high-performance transformer-feedback RF-ICs.

Reference

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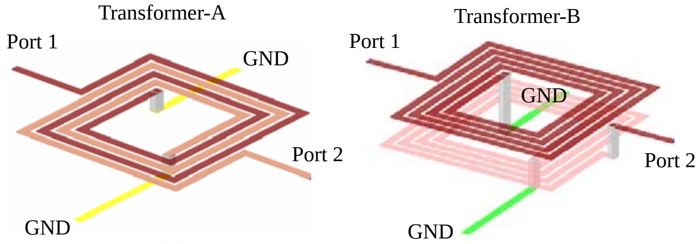
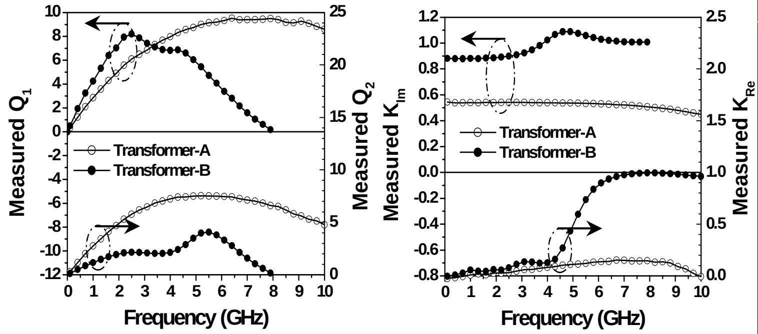


(a) (b)

Fig. 1 The 3D schematic diagrams of (a) transformer-A, and (b) transformer-B.

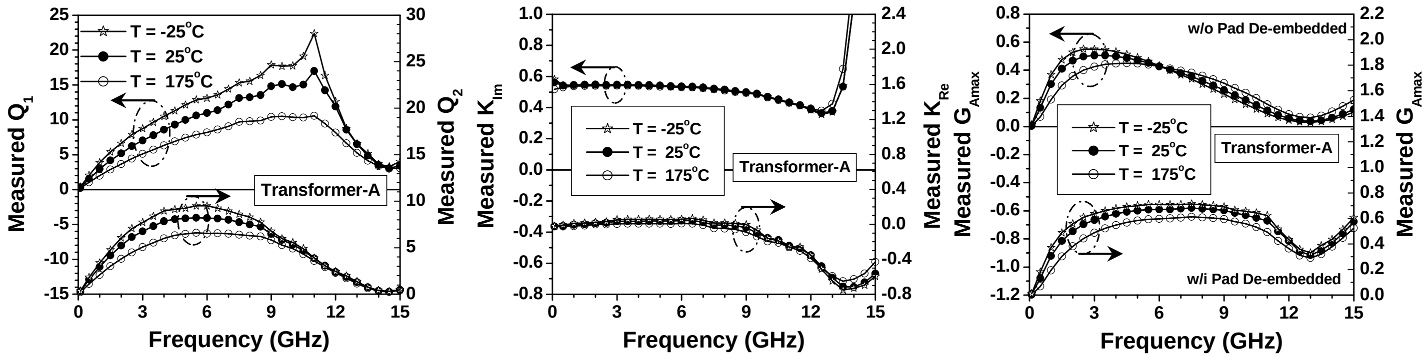


(a) (b)

Fig. 2 The measured (a) Q_1 and Q_2, and (b) K_{IM} and K_{Re} of transformers A-B.

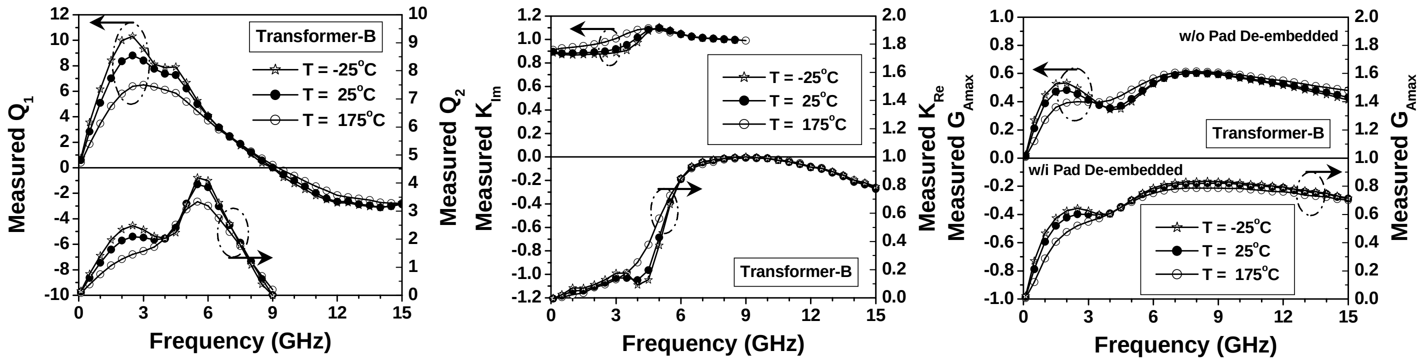
Table I Summary of the primary layout parameters and the extracted SSC parameters of transformers A-E.

Technology	0.18 μm 1P6M CMOS Process (substrate resistivity: 10 Ω·cm, substrate thickness : 750 μm)				
Transformer ID	A	B	C	D	E
Structure	Bifilar	Stacked (STD)	Stacked (offset)	Stacked (offset)	Stacked (offset)
W (μm)	10				
S (μm)	5	5	10	10	10
Turn number (N)	2	4	4	4	4
Turn Ratio	1:1	1:1	1:2	1:3	1:4
Primary Coil	M6	M6	M5	M5	M4
Secondary Coil	M6	M5	M6 & M4	M6 & M4-M3	M6-M5 & M3-M2
Overall Dimension (μm×μm)	240×240				
Inner Dimension (μm×μm)	100×130		60×70		60×60
Range (GHz)	0.1 - 10	0.1 - 8	0.1 - 3	0.1 - 1.45	0.1 - 1.425
R_{s1} (Ω)	3.9	7.26	23.37	23.69	24.38
L_{s1} (nH)	1.89	5.86	4.08	4.15	4.10
R_{s2} (Ω)	4.1	27.12	25.53	48.35	69.20
L_{s2} (nH)	1.94	5.58	13.51	28.53	49.70
M (nH)	1.03	4.78	6.39	9.80	12.82
K	0.58	0.89	0.861	0.900	0.898
C_p (fF)	62.7	633.4	204	358.2	394.6
C_{ox1} (fF)	54.3	167.4	121.4	148.2	146.6
C_{ox2} (fF)	57.3	186.1	436	691.6	761.4
C_{sub1} (fF)	4.3	30.0	125.9	145.8	162.8
R_{sub1} (Ω)	2277.2	3167.7	206.6	768.6	851
C_{sub2} (fF)	10.9	50.4	417.3	376.4	269
R_{sub2} (Ω)	1660.2	3248.1	1444.4	1520.8	2027.7



(a) (b) (c)

Fig. 3 The measured (a) Q_1 and Q_2, (b) K_{IM} and K_{Re}, and (c) G_{Amax} (both before and after the test pads were de-embedded) of transformer-A at various temperatures (-25°C, 25°C, and 175°C).



(a) (b) (c)

Fig. 4 The measured (a) Q_1 and Q_2, (b) K_{IM} and K_{Re}, and (c) G_{Amax} (both before and after the test pads were de-embedded) of transformer-B at various temperatures (-25°C, 25°C, and 175°C).