Experimental Investigation of Differential Line Inductor for RF Circuits with Differential Structure

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Abstract— **A Differential line inductor is proposed for a differential power amplifier. The proposed differential line inductor is composed of two conventional line inductors rearranged to make the current direction of the two line inductors identical. The proposed line inductor is simulated with a 2.5-D and a 3-D EM simulator to verify its feasibility with the substrate information in a 0.18-μm RF CMOS process. The inductances of various line inductors implemented with printed circuit boards were measured. The feasibility of the proposed line inductor was successfully demonstrated.**

Index Terms— **Line inductor, Spiral inductor, RF circuit.**

I. INTRODUCTION

THE INDUCTOR is an essential component of an RF circuit. However, the low quality factor and bulky size of an integrated inductor degrades the performances and increases the cost of RF circuits. Particularly, the integrated inductor often becomes an obstacle in the design of a RF CMOS power amplifier, although the frequency performance of CMOS itself can be compared to the active device of a compound semiconductor. CMOS technology has been regarded as unsuitable in the design of a watt-level power amplifier.

Recently, a distributed active transformer was proposed to develop a watt-level RF CMOS power amplifier [1-2]. The distributed active transformer solved the various problems of RF CMOS power amplifiers. Thus, the distributed active transformer has been studied widely for output matching networks of a RF CMOS power amplifier with watt-level output power [3-7].

Although the output matching networks of a RF CMOS power amplifier are solved using a distributed active transformer, the inductance of inter-stage matching networks with a high quality factor and compact size remain as a problem to be solved. In particular, the inter-stage inductance is the key component in a multi-mode power amplifier; it has become a popular means of increasing the efficiency in the low-output-power region.

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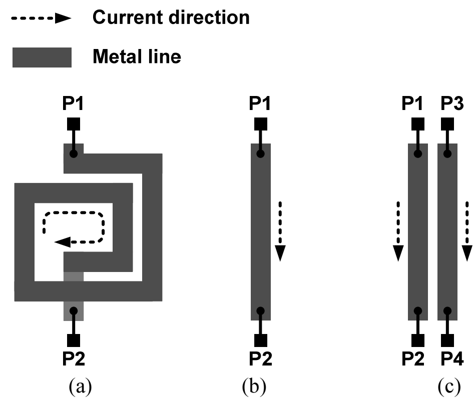


Fig. 1. (a) Spiral inductor, (b) line inductor (After [7]), (c) proposed differential line inductor

The low power matching network of a multi-mode power amplifier needs high inductance in general [5-7]. An improvement to the low power efficiency of a multi-mode power amplifier will be degraded with a conventional spiral-type inductor for an inter-stage matching network due to the low quality factor of the inductor.

In this work, a differential line inductor to solve the low quality factor and bulky size of a conventional spiral-type inductor is proposed for inter-stage matching networks. The differential line inductor is suitable for a differential RF circuit. The performances levels of the proposed differential line inductor are compared with those of a spiral-type inductor and line inductor.

In Section II, the conventional line inductor, the spiral inductor, and the proposed differential line inductor are described. In Section III, the results of simulations involving the inductors are analyzed. Finally, the measured inductances of the inductors designed on a printed circuit board are shown.

II. CONVENTIONAL INDUCTOR VS. DIFFERENTIAL LINE INDUCTOR

A. Conventional Inductor

Figure 1 shows a conventional spiral inductor, a line inductor, and the proposed differential line inductor. The spiral inductor is most popular component for inductance in a matching network. However, the spiral inductor has a low quality factor and a bulky size.

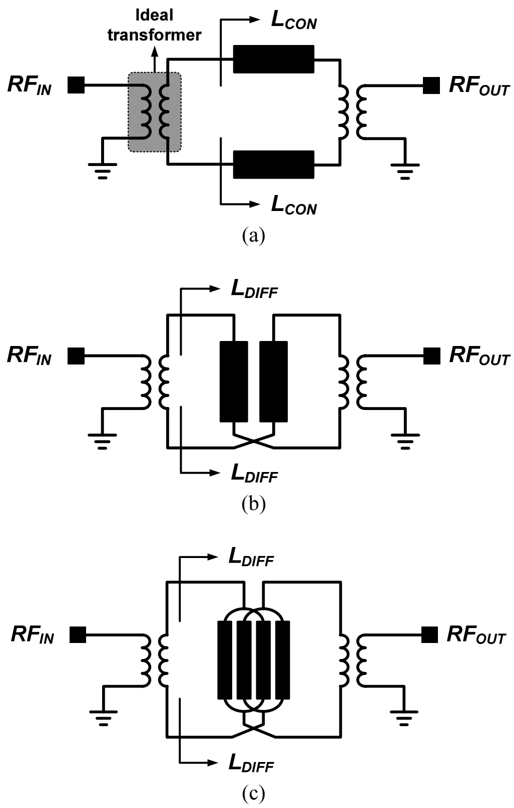


Fig. 2. (a) Conventional line inductor (After [7]), (b) proposed differential line inductor, and (c) proposed interdigitated differential line inductor

Another component for inductance is the line inductor. The quality factor of a line inductor is higher than that of a spiral inductor in general. The line inductor is popular for millimeter wave circuits. However, a conventional line inductor is not suitable for 1-2 GHz circuits due to its low inductance.

B. Proposed Differential Line Inductor

To solve the problems associated with spiral and line inductors, the differential line inductor is proposed. The benefits of the differential line inductor are its high inductance, high quality factor and compact size. The differential line inductor is suitable for RF circuits with a differential structure. Generally, RF CMOS power amplifier is designed with a differential structure to remove the gain-reduction problems that are induced by the bond wires. If series inductance is required for an inter-stage matching network in a RF CMOS power amplifier, two inductors are needed, as shown in Fig. 2 (a). Thus, the chip area becomes bulky. To design the proposed differential line inductor, the layout shown in Fig. 2 (a) was modified to that shown in Fig. 2 (b). The two conventional line inductors in Fig. 2 (a) were rearranged to make the current directions of the two line inductors identical, as shown in Fig. 2 (b). The magnetic fields generated by the two line inductors influence each other as a result. As the current directions of the two line inductors are identical, the mutual inductance levels of the two line inductors are increased.

Thus, the inductance of the differential line inductor will be higher than that of a conventional line inductor. Given that the parasitic resistance of the proposed differential line inductor is identical to that of a conventional line inductor, the quality factor of the differential line inductor will be higher than that of the conventional line inductor.

III. SIMULATION AND MEASUREMENT RESULTS OF THE DIFFERENTIAL LINE INDUCTOR

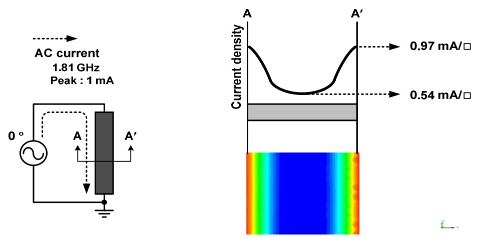
A. Simulation Results

To verify the performance of the differential line inductor, the performance levels of the conventional line inductor and several differential line inductors were simulated using the substrate information in a 0.18-μm RF CMOS process. The lengths of various line inductors were fixed at 500 μm for a fair comparison of the performance levels. The spacing between the metal lines of the differential line inductor was 3 μm. The thickness of the metal line was 2.34 μm.

2.5-D and 3-D electromagnetic simulators were used to check the inductances, quality factors, and maximum available gains of the different line inductors. Figure 3-5 shows the simulated current density when a 1.81-GHz signal is entered through the different line inductors. For the conventional line inductor, as shown in Fig. 3, a 1 mA 1.81-GHz signal was entered. The AC current of the conventional line inductor flows through the edge of the metal line as a consequence of the skin effect and a proximity effect. The current density of the conventional line inductor is shown in Fig. 3.

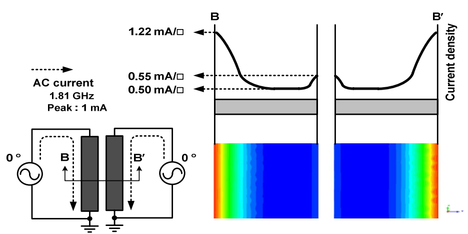
Figure 4 shows the EM simulation results of the proposed differential line inductor. The AC currents of the two metal lines in Fig. 4 must run in the same direction to create the differential line inductor. Thus, most of the AC current flows through the outer edges of the metal lines according to the proximity effect. The current densities are slightly increased in the inner edges of the metal lines according to the skin effect. Figure 5 shows the EM simulation results of the other proposed differential line inductor.

Under the same simulation conditions, the quality factors, maximum available gains, and inductance levels were checked. The s-parameters of the various line inductors were extracted using a 2.5-D EM simulator. Using the extracted s-parameters, the quality factors, maximum available gains, and inductances were simulated with the schematics shown in Fig. 6-8. Figure 6



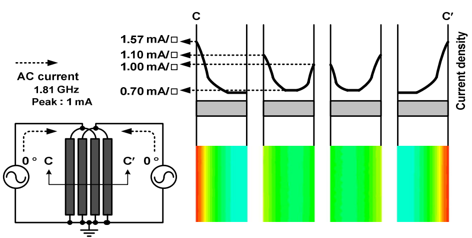
(a) (b)

Fig. 3. Conventional line inductor (a) simplified circuit for EM simulation, (b) simulated current density at the metal line



(a) (b)

Fig. 4. Differential line inductor (a) simplified circuit for EM simulation, (b) simulated current density at the metal line



(a) (b)

Fig. 5. Interdigitated differential line inductor (a) simplified circuit for EM simulation, (b) simulated current density at the metal line

shows the simulated inductance levels of the various line inductors. The parameter N is the number of split metal line of differential line inductor. The inductance levels of the proposed line inductors were simulated at a higher rate compared to those of the conventional inductor, as shown in Fig. 6. At 1.81 GHz, the inductances of the proposed differential line inductors were increased by approximately 53% compared to the conventional inductor. The inductance levels of two types of differential line inductors were nearly identical.

Figure 7 shows the maximum available gains of the line inductors. The RF current flows over the surface of the metal line as a result of the skin effect. Thus, to reduce the parasitic resistance of the metal line, the surface of the metal line must be increased. The surfaces

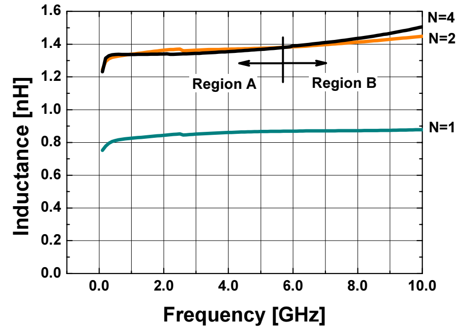


Fig. 6. Simulated inductance levels of various line inductors

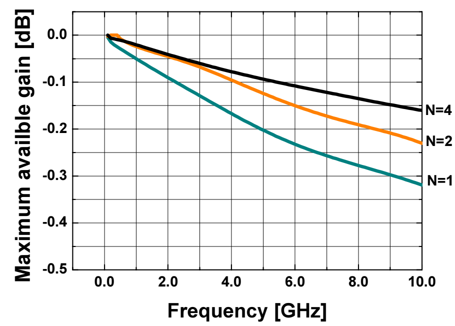


Fig. 7. Simulated maximum available gains of various line inductors

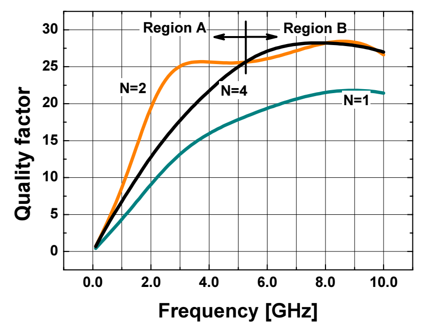
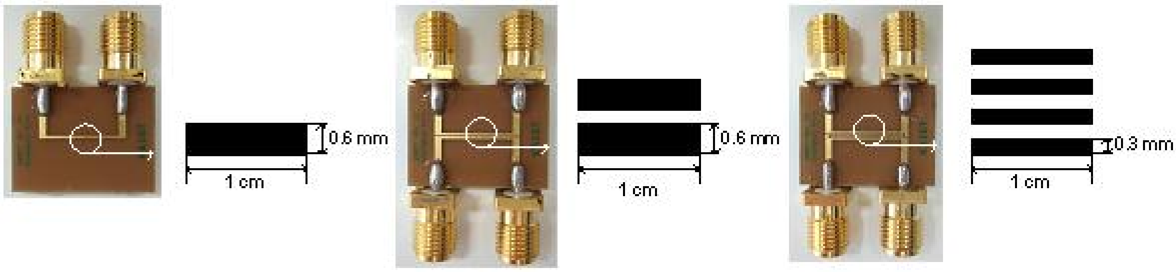


Fig. 8. Simulated quality factors of various line inductors

of the proposed differential line inductors are larger than that of the conventional line inductor. Thus, the parasitic resistance values of the differential line inductors are lower than that of the conventional line inductor. The differential line inductor shown in Fig. 5 has a larger surface compared to that of the differential line inductor shown in Fig. 4. Thus, the parasitic resistance of the conventional line inductor is highest among the three line inductors. The differential line inductor shown in Fig. 5 has lowest parasitic resistance among three line inductors. The parasitic resistance of the line inductors affects the maximum available gains directly, as shown in Fig. 7.



(a) (b) (c)

Fig. 9. (a) Conventional line inductor, (b) differential line inductor, and (c) interdigitated line inductor

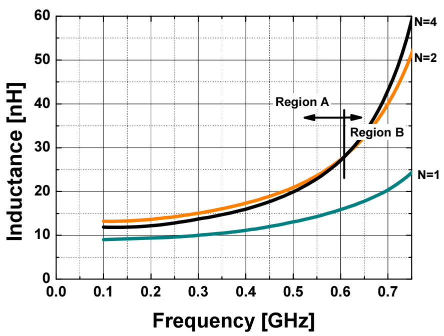


Fig. 10. Measured inductance levels of various line inductors

Figure 8 shows the quality factors of the line inductors. The quality factors of the differential line inductor are higher than that of the conventional line inductor owing to the increased mutual inductance levels of the differential line inductors. At Fig. 6, Fig. 8, and Fig. 10, the graphs are divided between Region A and Region B for convenience. In region A, the parasitic resistance of the differential line inductor shown in Fig. 4 is nearly identical to that of the differential line inductor shown in Fig. 5. However, the inductance of the differential line inductor shown in Fig. 4 is slightly higher than that of the differential line inductor shown in Fig. 5. Thus, in region A, the quality factor of the differential line inductor shown in Fig. 4 is higher than that of the differential line inductor shown in Fig. 5.

In conclusion, the inductance levels of the proposed differential line inductors shown in Fig. 4 and Fig. 5 are higher than that of the conventional line inductor shown in Fig. 3 on account of the mutual inductance.

B. Measurement Results

To verify the feasibility and the simulation results of the proposed differential line inductor, various line inductors were designed using a printed circuit board (PCB). A four-port vector network analyzer was used to measure the different line inductors. Fig. 9 shows the implemented differential line inductors. The metal thickness of the PCB is 25 μm and the substrate thickness is 1000 μm. The design parameters of the different line inductors are shown in Fig. 9.

Fig. 10 shows the measured inductance levels of the designed line inductors. As predicted in the simulation results, the proposed line inductors have higher inductance levels than the conventional line inductor. Thus, the feasibility of each of the proposed line inductors is verified.

The proposed differential line inductor has high inductance and a high quality factor with a compact size compared to a conventional line inductor. The proposed line inductor is suitable for the inter-stage matching networks of RF CMOS circuits with a differential structure.

IV. CONCLUSIONS

A differential line inductor is proposed for a differential power amplifier. The proposed differential line inductor is composed of two conventional line inductors rearranged to make the current direction of the two line inductors identical. The proposed line inductor was simulated with a 2.5-D and a 3-D EM simulator to verify its feasibility with the substrate information in a 0.18-μm RF CMOS process. The inductance levels of various line inductors implemented with a printed circuit board were measured. The proposed differential line inductor has high inductance and a high quality factor with a compact size compared to a conventional line inductor. The proposed line inductor is suitable for the inter-stage matching networks of RF CMOS circuits with a differential structure.

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Changkun Park received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2001, 2003, and 2007, respectively. He was with the Advanced Design Team, Dynamic Random Access Memory (DRAM) Development Division, Hynix Semiconductor Inc., where he was involved with development of high-speed I/O interfaces of DRAMs. In 2009, he joined the School of Electronic Engineering, Soongsil University, Seoul, Korea, as a faculty member. His research interests are microwave integrated circuits and systems including power amplifiers for mobile communications.