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Area Efficient and Symmetric Design of Monolithic Transformers for Silicon RF ICs*

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Abstract

A novel monolithic transformer structure, mixed coupling structure, is proposed and compared with other more conventional structures, side-coupling and vertical-coupling structure. The proposed mixed-coupling structure shows the best performance in the aspects of symmetry, area efficiency, and insertion loss. The structures of the three transformers along with the measurement results are presented and analyzed.

I. INTRODUCTION

Silicon based RF ICs are becoming ever increasingly competitive in the wide gigahertz frequency range applications. With technology scaling, the silicon processes provide high frequency active devices for use in RF applications (e.g., 800 MHz - 2.5 GHz). Although significant progresses has been made, the low quality passive components presents a major huddle for the demand of low cost, low supply voltage, low power dissipation, and low noise implementation of RF integrated circuits.

Monolithic spiral transformers has been used in many microwave and RF ICs to perform impedance matching, signal coupling, phase splitting, etc. Some of the example are low-loss feedback and single-ended-to-differential signal conversion in a 1.9 GHz receiver front end [1], matching and coupling in balanced amplifiers [2, 3], and in an image rejection mixer [4].

In this paper, a novel monolithic spiral transformer is proposed and compared with the more conventional structures. The new structure demonstrates better performance, compare to the conventional structures, in the aspect of symmetry, area efficiency, and insertion loss. The three transformer structures, including the new structure, are described and the measurement results are introduced and analyzed.

II. TRANSFORMER DESIGN

Limiting the discussions to 1 : 1 transformer, an ideal transformer may be defined as one that is transparent to the source and load and can deliver 100% power from the source to the load without the direct DC connection between them. In order to get performances close to ideal, transformers are expected to have 100% magnetic coupling between the primary and secondary coils, no power losses through the adjacent materials, infinite inductances for each coil, and no resistive losses through the coil conductors. As it is well known, the real world monolithic transformers have problems such as the finite amount of metal line resistances, the finite inductances of the primary and secondary coils, power losses through the substrates especially with silicon processes, and the matter of how to achieve 100% coupling.

Figure 1 ~ 3 shows the three transformer structures that has been designed and fabricated. The side-coupling structure (SCS), shown in Fig. 1, is the most common layout used in many RF ICs [5, 6, and 7]. The SCS requires double metal process and the magnetic fluxes are coupled through the inter-wounded metal lines. As shown in Fig. 1, SCS is symmetric. One problem with the SCS is the area efficiency. As the primary and the secondary coils have to be placed on every other lanes, this structure takes more silicon areas compare to the other structures, for the same amount of coil inductances. Furthermore, the primary and secondary coils of the SCS structure are not as closely placed as the other two, hence, the mutual coupling factors are expected to be worse.

Compare to the SCS, the vertical-coupling structure (VCS), shown in Fig. 2, has the advantage of area efficiency and the higher mutual coupling by placing the primary on top of the secondary coil. Typically, the metal-to-metal spacing are less than 1 micron. Considering the pressure for the low cost implementation of the RF ICs, by no means, the advantage of the area efficiency shown in Fig. 2 can not be overlooked. However, the VCS have a couple of problems. The VCS is not symmetric. As can be seen from Fig. 2, not only the secondary coil (L2 in Fig. 2) is placed closer to the silicon substrate but also the thicknesses of the primary and secondary coils are often different in typical integrated circuit processes. With many RF applications, the non-symmetric nature of the VCS can be a limiting factor for its usefulness. Moreover, the VCS, as can be seen from Fig. 2, requires triple metal process which can be another limitation.

Figure 3 shows the mixed-coupling structure (MCS) proposed by the author. Like VCS, The MCS has the advantage of the area efficiency. MCS is expected to show good mutual couplings, comparable or even better than the VCS, not only by the placement of the primary on top of the secondary but also by the cross-placement of the coils as shown in Fig. 3. Moreover, the MCS is nearly symmetric and can be implemented with just double metal process. Basically, the MCS is a mix-up of the previous two structures and takes advantage of the strong points of each structure.

III. MEASUREMENT RESULTS AND DISCUSSIONS

The three different transformer structures are fabricated using a 0.35-micron quadruple-metal CMOS

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process. The thicknesses of the 1st, 2nd, and 3rd metals are about 0.6 micron and the 4th metal thickness is about 1 micron. The resistivity of the 1st, 2nd, and 3rd metals are 80 m/square and the 4th metal resistivity is 40 m/square, respectively. Figure 4 shows the photo of the fabricated transformers. In Fig. 4, the SCS uses the 3rd and 4th metal, while the VCS uses the 2nd, 3rd, and 4th metals, and the MCS uses the 3rd and 4th metals only. The MCS transformer is also laid out utilizing all four layers of the process: 1st and 2nd metals as the secondary and the 3rd and 4th metals as the primary coils (call it as MMCS: multiple-layered mixed coupling structure).

Figure 5 shows the *S*21 as a function of frequency for the transformer structures described above. As can be seen from Fig. 5, the VCS and MCS show about the same performance. This means that the two structures have about the same mutual coupling, contrary to the better coupling expected from the MCS. This tells us that the inter-layer coupling dominates the overall mutual couplings rather than the coupling of the one metal placed on top of the other. The primary and secondary coils of MCS can have higher series resistances by the more frequent switching between the 3rd and 4th metals. However, the *S*11 and *S*22 measurement show that the resistance added by the via connections are negligible. As expected, the SCS shows the worst performance of all. This is mainly because of the lower inductances of the primary and secondary coils of the SCS for the given amount of transformer size. It can be seen that the resistive loss of the spiral coils plays a major role for the increase in the transformer loss. In Fig. 3, the *S*21 of the MMCS is about 1 dB higher than that of the MCS near 1.8 GHz. The *S*21 for MMCS is about -3 dB near 1.8 GHz.

Figure 6 compares the *S*11 and *S*22 of the VCS and MCS. As shown in Fig. 3, the MCS is not exactly symmetric, so that the *S*11 and *S*22 of the MCS show slight discrepancies, yet the MMCS show excellent matching. This requests for further investigation. The MCS does shows much better *S*11 and *S*22 matching compare to that of the VCS.

IV. CONCLUSION

A novel monolithic spiral transformer structure is proposed and compared with the more conventional structures. The proposed structure requires only double metal process, yet more area efficient than the conventional structures by the tactful placing of one layer on top of the other. Moreover, the new structure is symmetric and shows minimum loss. The layout and measurement results of the newly proposed transformer along with two more conventional structures are presented and analyzed.

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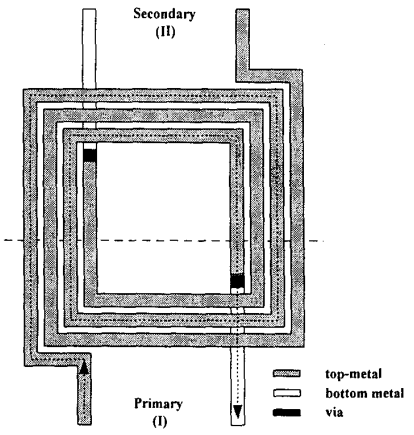

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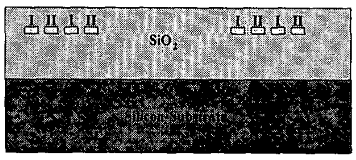

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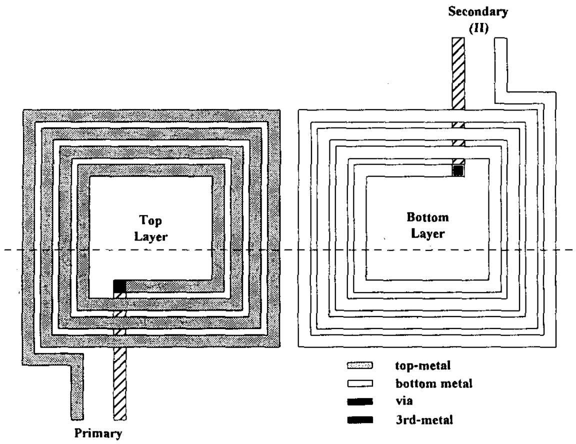
Fig. 1 The structure of the conventional side-coupling monolithic transformer (SCS).



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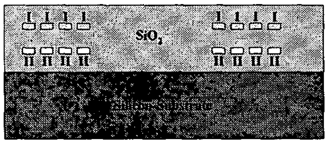

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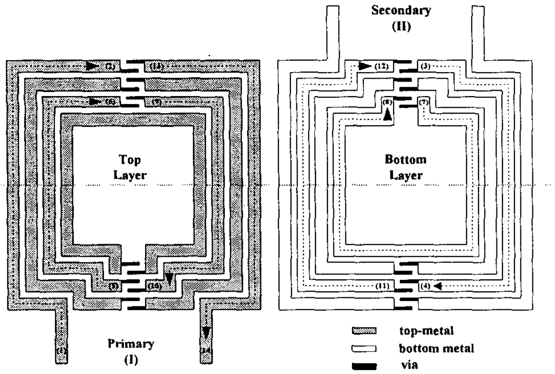
Fig. 2. The structure of the vertical-coupling monolithic transformer (VCS).



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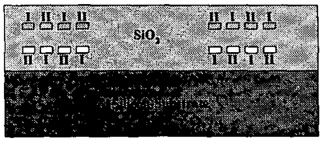

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Fig. 3. The structure of the mixed-coupling monolithic transformer (MCS). Dashed arrow represents the primary and secondary signal flow.

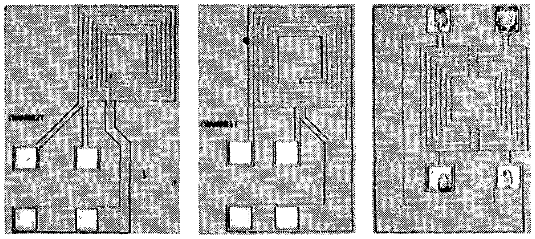


Figure 4. Photo of the fabricated monolithic transformers: (a) double-layered side-coupling structure (SCS), (b) triple-layered vertical-coupling structure (VCS), and (c) double-layered mixed-coupling structure (MCS).

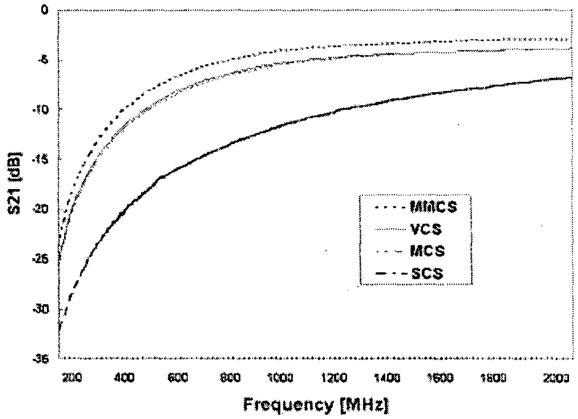
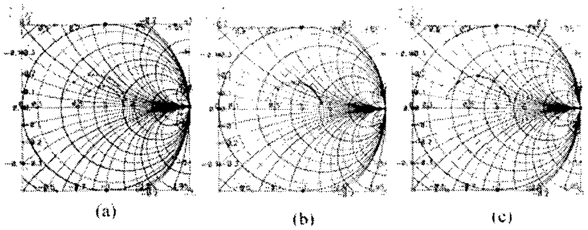


Figure 5: The measured S_{21} versus frequency of the transformers. dash: multiple-layered mixed-coupling structure (MMCS), solid: vertical-coupling structure (VCS), dash double-dot: mixed-coupling structure (MCS), dash dot: side-coupling structure (SCS).



(a) (b) (c)

Figure 6. The measured S_{11} and S_{22} of the transformers as a function of frequencies. (a) VCS, (b) MCS, and (c) MMCS.