Abstract
For high frequency radar applications in the millimeter wave range, small standard planar spiral inductors are used. A 3D inductor that structurally creates more distance between the turn segments carrying currents in opposite directions is presented. As compared to standard planar spiral inductor of identical dimensions, this structure provides an improvement in quality factor by 23-25% with added improvement in inductance by 19-23%. This inductor is useful for radar applications in the frequency band 30-100 GHz. This inductor is realized using standard Taiwan Semiconductor Manufacturing Co. Ltd (TSMC) 0.25 μmeter, one poly and four metal CMOS process technology parameters. Results are presented using SONNET EM simulator (Evaluation).

Indexing terms: Inductance, mutual Inductance, quality factor, turn segments, VCO’s.

I. INTRODUCTION
For radio frequency integrated circuits, inductors are one of the basic components and their performance affects significantly the overall circuit performance of VCO’s, LNA’s and impedance matching circuits. Silicon integrated inductors are finding wide applications in GHz frequencies. Standard planar inductors are reported in the literature [1-2]. The quality factor is improved by layout optimization with multiple turn widths or taking larger outer turn width has been reported [3-4]. Inductor with large quality factor and high self-resonance frequency is reported [5]. A miniature inductor with high self-resonance frequency that occupies only 16% of the silicon area is reported [6]. All these inductors are used in LAN’s, VCO’s and impedance matching networks. For high frequency radar applications in the mm wave range, small standard planar spiral inductors are used [7]. The mutual inductance between the conductors is a function of the distance between the conductors and their dimensions. The mutual inductance decreases as the distance between the conductors increases. Based on this, we propose a 3D inductor structure for millimeter wave applications.

II. INDUCTANCE CALCULATION
In the proposed structure, one half part of the spiral is in layer-2 and the remaining part of the spiral inductor is in layer-1 as shown in the Fig. 1. This creates more distance between the turn segments carrying currents in opposite directions structurally. This structure is useful for inductors whose outer diameter is less than 50 μmeter. The tunability of the tunable spiral inductor [8] can be further enhanced by using 3D inductor as base inductor. While simulating the inductor using EM simulator, the resistivity of the silicon is 8.30 ohms-cm, the conductivity of the metal is 5.8 \times 10^7 s/m, the metal-to-metal oxide thickness is 5.02 μmeter and metal to substrate thickness is 3.76 μmeter.

Fig. 1 3D Inductor
algorithm for computing the inductance of planar rectangular spirals [9]. The Greenhouse method states that the overall inductance of a spiral can be obtained by computing the self-inductances of individual segments and positive and negative mutual inductance between all possible wire segment pairs. For instance an N turn spiral has 4N self-inductance terms, 2N (N-1) positive mutual inductance terms, and $2^2N$ number of negative mutual inductance terms. Although many empirical formulas exist in literature for the estimation of spiral inductors, Greenhouse method provides a good approximation in finding the inductance. Further accuracy can be obtained by using the data filling techniques [2]. The mutual inductance between any two conductors, which is a part of the structure, is also calculated after solving the integration using Maclausin’s theorem. This is called hereafter integration method as explained below. Consider, two conductors separated by a distance “d” and carrying currents in to the conductor along z-axis with current magnitudes as $I_1 e^{-\beta_1 z}$ and $I_2 e^{-\beta_2 z}$ as shown in the Fig. 2.

\[ \vec{A}(x,y,z) = \frac{\mu_0 I}{4\pi} \left( \frac{e^{-\beta_1 z}}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} \right) \]  \hspace{1cm} (1)

Here, the dimensions of the conductors, part of the spiral, are such that, the cross section of the conductor is infinitesimally small as compared with the length of the conductors. With this assumption, if the current is uniform through out the conductor and the conductor length is less than the wavelength, then the above equation becomes

\[ \vec{A}(x,y,z) = \frac{\mu_0 I}{4\pi} \left( \frac{e^{-\beta_2 z}}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} \right) \]  \hspace{1cm} (2)

The magnetic flux density $B$ and the vector magnetic potential $\vec{A}$ are related by the equation

\[ \vec{B} = \nabla \times \vec{A} \]  \hspace{1cm} (3)

The total magnetic flux associated with the second conductor, having length $L_2$, due to first conductor carrying $I_1$ is given by

\[ \tilde{\phi}_{21} = \int_{S} \vec{B} \cdot ds \]  \hspace{1cm} (4)

Using Stokes theorem, the above equations becomes

\[ \tilde{\phi}_{21} = \int_{\partial S} \vec{A}_2 (d,0,z) \cdot dz \]  \hspace{1cm} (5)

\[ \tilde{\phi}_{12} = \int_{\partial S} \vec{A}_2 (d,0,z) \cdot dz \]  \hspace{1cm} (6)

Expanding the integrand using the Maclausin’s theorem up to $4^{th}$ order terms and then solving the integration, the total flux associated with the second conductor due to first conductor carrying the current $I_1$ is obtained. The mutual inductance between the conductors is given by the expression

\[ M_{12} = \frac{\mu_0 I_1}{4\pi} \frac{\tilde{\phi}_{12}}{I_2 e^{-\beta_2 z}} \]  \hspace{1cm} (7)

The mutual inductance calculated from the Greenhouse method and the integration method is shown in the Fig. 3.
The results show that the mutual inductances are almost equal in both the methods. Hence, we will consider the method adopted by the simulator. Here the EM simulator calculates the inductance and quality factor between any two ports by assuming a PI-model. The quality factor is obtained using 
\[ \text{quality factor} = \frac{\text{imag}(Y_{mn})}{\text{real}(Y_{mn})} \]
(ref. Sonnet manual) and inductance is obtained using 
\[ L = \frac{1}{2\pi f} \text{Im} \left( \frac{1}{Y_{12}} \right) \].

The simulator approximates the inductance and quality factor of the considered inductors by considering the cubical dimension of the conductor segments such as the width, length and thickness of the conductors.

### III. RESULTS

Simulations are carried out on both the inductors discussed namely a standard planar spiral inductor and a 3D inductor having identical dimensions. The dimensions of the inductor are the number of turns (N), spacing between the turns (S), thickness of the conductor (t), outer diameter (od) and the area occupied by both the inductors. Results are obtained using SONNET EM simulator (Evaluation). The simulation result shown in Fig. 4 and Fig. 5 exhibit that, the smaller outer diameter inductors have higher inductance and quality factor over wider outer diameter inductors. As we increase the spacing between the turns of the spiral inductor, the amount of magnetic coupling is reduced.
Inductor are reduced. This is also demonstrated in simulation results, as shown in Fig. 6 and Fig. 7 respectively. If we increase the width \(w\) of the 3D inductor, it is reasonable to increase the quality factor and to decrease inductance.

![Fig. 6](image)

**Fig. 6** The inductance of the 3D inductor structure for different spacing. The dimension of the inductor outer diameter \(od\) = 10 micrometers, width of the conductor \(w\) = 0.8 micrometers, spacing between the turns \(s\) = 0.4 and 0.5 micrometers, thickness of the conductor \(t\) = 0.6 micrometers, number of turns \(N\) = 4.

![Fig. 7](image)

**Fig. 7** The quality factor of the 3D inductor structure for different spacing between the turns. The dimension of the inductor outer diameter \(od\) = 10 micrometers, width of the conductor \(w\) = 0.8 micrometers, spacing between the turns \(s\) = 0.4 and 0.5 micrometers, thickness of the conductor \(t\) = 0.6 micrometers, Number of turns \(N\) = 4.

The variation in inductance and quality factor for different turn widths against frequency is shown in Fig. 8 and Fig. 9 respectively. The simulation results also demonstrate that as we increase the turn width of the inductor, the quality factor is increased and consequently, the inductance is reduced.

![Fig. 8](image)

**Fig. 8** The inductance of the 3D inductor structure for different widths \(w\) of the spiral inductor. The dimension of the inductor outer diameter \(od\) = 15 micrometers, spacing between the turns \(s\) = 0.4 micrometers, thickness of the conductor \(t\) = 0.6 micrometers, Number of turns \(N\) = 4.

![Fig. 9](image)

**Fig. 9** The quality factor of the 3D inductor structure for different widths \(w\) of the spiral inductor. The dimension of the inductor outer diameter \(od\) = 15 micrometers, spacing between the turns \(s\) = 0.4 micrometers, thickness of the conductor \(t\) = 0.6 micrometers, Number of turns \(N\) = 4.
The percentage of variations in inductance and quality factor for different outer diameters against frequency is shown in Fig. 10 and Fig. 11 respectively. These simulation results clearly demonstrate that the smaller outer diameter inductors have higher inductance and quality factor over wider diameter spiral inductors.

![Fig. 10](image1)

**Fig. 10** The percentage of variation of the inductance of the 3D inductor over planar inductor against frequency for different outer diameters \(0d=10\) micrometers, \(od=15\) micrometers, with same width \((w)=1.0\) micrometer, spacing \((s)=0.4\) micrometers, thickness \((t)=0.6\) micrometers, Number of turns\((N)=4\).

The simulated results show that the 3D inductor shows improvement in inductance by 19-23% and improvement in quality factor by 23-25% over standard planar spiral inductor for identical dimensions.

**IV. DISCUSSIONS**

Simulations are obtained in order to validate the effect of the spacing \((s)\) between the turns of the spiral inductor, effect of turn width \((w)\) of the spiral inductor and also the effect of outer diameter \((od)\) on quality factor and inductance of the 3D inductor and standard planar spiral inductor. The result shows that (refer the Fig. 4 and Fig. 5) there is an improvement in inductance by 19-23% and improvement in quality factor by 23-25% for the simple 3D inductor structure over planar spiral inductor for smaller outer diameters. If the spacing between the turns of the 3D inductor is increased, the amount of magnetic coupling will be reduced. Due to reduced magnetic coupling, the inductance and quality factor of the spiral inductor is reduced. This is also demonstrated in the simulation results as shown in Fig. 6 and Fig. 7 respectively. If we increase the width \((w)\) of the 3D inductor, it is reasonable to increase the quality factor and to decrease inductance. The simulation results shown in Fig. 8 and Fig. 9 also reveal the same effect. In the 3D inductor, because of the more distance between the conductor segments carrying currents in opposite directions, the mutual inductance is reduced. Hence, there is increase in overall inductance and quality factor. Because of the structural advantage of 3D inductor, for small outer diameters the increase in inductance and quality factor will be more. The simulation results also display the same as shown in Fig. 10 and Fig. 11, where the percentage of increase in inductance and quality factor over planar inductor is plotted against frequency. For small inductors, whose the outer diameters are less than 50 micron meters square, the 3D inductor is more suitable for mm meter wave radar applications over simple standard planar inductors.

**V. CONCLUSIONS**

The simulated results are studied for the proposed 3D inductor and a standard planar...
inductor by changing the spacing between the
turns, the turn widths and outer diameter. From
the simulation results, the 3D inductor shows
an improvement in inductance and quality
factor over standard planar spiral inductor of
identical dimensions. Hence, for a small square
spiral inductor whose area of cross section is
less than $50 \times 50 \, \mu$ meters square, this 3D
inductor is more suitable for radar applications
in the 30-100 GHz frequency band.

VI. REFERENCES

[1] Patrick Yue, SI Simon Wong “Physical modeling of
spiral inductors on silicon,” IEEE Tran. On Electron

[2] Sunder Rajan, Maria Mar Hershenson, Stephen P.
Boyd and Thomas H. Lee, “Simple accurate
expressions for planar spiral inductors,” IEEE
Journal of Solid state circuits, vol.34, pp.1419-1424,
1999.

[3] Jose M Lopez Samier and Joan Bausells
“Improvement of the Quality factor of RF Integrated
Inductors by Layout Optimization,” IEEE
Microwave Theory and Techniques, vol. 48, no. 1,
pp 76-83, Jan 2000.

of metal of various widths in spiral inductor,” IEEE
Trans. Electron Devices, vol. 51, no. 8, pp 1343-
1346, August 2004.

[5] Alireza Zolfaghari, Andrew Chan and Behzad Razavi,
“Stacked Inductors and Transformers in CMOS
Technology,” IEEE Journal of solid state circuits,
vol. 36, no. 4, April 2001.

“Miniature 3D inductors in standard CMOS
Process,” IEEE Journal of solid state circuits,
vol.37, no. 4, pp 471-479, April 2002.

[7] T.Diskson, M.A. LaCroix at. al “Si-based Inductors
and Transformers for 30-100 GHz Applications,”

tunable multi turn spiral inductors for RF
Applications,” Microwave and Optical Technology

Microelectronic inductors,” IEEE Transactions Parts,