High performance CMOS based LC-VCO design using high Q-factor, field shield layered substrate inductor

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Abstract - This work reports a CMOS based current reuse voltage controlled oscillator (VCO) using the design of ferrite integrated inductor on a three layered substrate in order to obtain lower phase noise and to improve the FOM of the VCO. This work is focused on improving Q-factor and L-density of the inductor that is to be used in the VCO by the enhancement of the magnetic properties of the inductor core, optimizing geometry of the core as well as conductor and by isolation of the substrate. It is observed that the proposed ferrite integrated inductor with field shield substrate layer improves the Q-factor by 53.8% and L-density by 78.1% as compared to air core inductor. The 65 nm CMOS based current reuse LC-VCO designed using the proposed inductor operates in the (2.27-2.79) GHz range. The proposed VCO exhibits lower phase noise of -115.96 dBc/Hz and -135.01 dBc/Hz at an offset of 1 MHz and 5 MHz respectively. Measurements show that the proposed VCO consumes a power of 2.85 mW from a supply of 1.1 V. This demonstrates that the proposed inductor can be beneficial for high performance RF ICs.

Index terms – Q-factor, ferrite-core inductor, field shield layer, substrate effects, phase noise, current reuse VCO

I. INTRODUCTION

With the advancements of CMOS technology in the recent years, there is an ever growing demand for high performance RF ICs in high speed, low power and high bandwidth communication systems. Technology scaling plays a pivotal role in advancement of ICs along with the use of circuit techniques. In particular, CMOS scaling has made RF CMOS IC design viable. VCO is identified as a challenging component in RF transceivers, and has been the driving force behind the endeavours to develop low power and compact RF ICs. VCOs are used for frequency conversion of the received signal to the intermediate frequency range with the help of a mixer in the front end of the receiver. On-chip spiral inductor is a key component of the VCO and is a deciding factor behind the performance parameters of the VCO namely phase noise, frequency tuning range and its figure-of-merit (FOM).

Conventional on-chip inductors suffer from large size, low quality factor and low L-density, resulting from conductor losses and substrate losses, which are inevitable. Eddy current loss and resistive loss contribute to the conductor loss. The conductor loss in an on-chip spiral inductor is directly proportional to its series resistance which increases with frequency. This effect is given as

$$\delta = \sqrt{\frac{\rho}{\mu f}}$$

where $\rho$ is the axial resistivity, $\mu$ is the permeability and $f$ is the operating frequency. As a result of decrease in $\delta$, series resistance increases. Eddy currents, contributes to both conductor and substrate losses, causing reduction in the spiral inductance and increases power losses in the substrate. In addition, the effect of parasitic capacitance due to oxide and other adjacent devices increases the complexity of inductor modeling. This motivates the inductor design to focus on reducing the conductor and substrate losses for improving the Q-factor and L-density. Non-availability of small size, high Q-factor and high L-density inductors pose a hindrance in the design of VCOs. Previous efforts have focused to develop various magnetic-core inductors for high Q-factor and high L-density, such as inductors with patterned magnetic dots. This design exhibits lower inductance value at high frequencies [1]. In other works, a grounded poly shield is used to reduce substrate loss and reported that they have not taken into account the process conditions [2,3]. In [4], solenoidal inductors with patterned permalloy magnetic cores were designed but suffered from eddy current losses at high frequencies. In [5], helical inductor with filtering method was designed but occupied large area. Moreover, the use of non-silicon substrates with high resistivity [6] to reduce substrate losses resulted in device failure due to non-uniform thermal expansion. In [7,8], the physical layout of the inductor was optimized but the relation between inductor performance and an individual variable was not known as it was based on multi-variable method.
In a nutshell, the design of high Q-factor and high L-density inductor requires both geometrical considerations of the core and conductor as well as minimization of substrate losses which were not taken into account simultaneously in [1] - [8]. The proposed work focuses on improving Q-factor and L-density by enhancement of the magnetic properties of the core, by determination of optimal geometrical variables of the conductor and by isolation of the substrate. This is achieved by designing a ferrite integrated inductor which helps to increase the magnetic flux in the core. Next the geometrical optimization of core and conductor is done within the area constraint i.e the analysis of variation of Q and L with respect to geometrical parameters such as thickness of the core, inner diameter and width of the spiral, helps in optimization of the inductor design. This is followed by inserting the field shield layer to decouple the substrate from inductor. The substrate is designed as a three layered structure in which the field shield layer is placed in between the high resistivity substrate and low resistivity substrate so as to arrest the carrier movement, thus reducing substrate losses and to avoid non-uniform thermal expansion problems.

Thus the proposed work aims in developing a CMOS based current reuse LC-VCO in 65 nm to operate in the UWB band using the optimized ferrite integrated spiral inductor to cater to the performance requirements of the VCO such as low power consumption, low phase noise, and a much improved FOM. The phase noise of VCO is decreased by enhancing the tank circuit Q-factor. The tank Q-factor is improved by the proper design of on-chip spiral inductor with reduced conductor and substrate losses. Based on these objectives, the paper is organised as follows: section II analyses the factors that affect the Q-factor and presents the circuit model of the optimized ferrite-core inductors, section III deals with the design of VCO incorporating the proposed inductors, section IV analyses the results of the proposed inductor and VCO parameters and section V is the conclusion.

II. DESIGN OF FERRITE INTEGRATED INDUCTOR

Integrated Passive Devices(IPD) technology uses three types of inductors, namely the planar spiral coil inductor, the solenoidal inductor, and the multi-level spiral inductor. Planar spiral inductors are mostly preferred for RF ICs compared to others due to their properties of high Q-factor, large value of inductance and small size. The proposed design of spiral inductor consists of four types of inductor with respect to filling of core, conductor geometry and substrate structure and are termed as L-1, L-2, L-3 and L-4.

A. Air-core inductor

The air-core inductor (L-1) is designed in HFSS with 2.5 turns, metal line width of 15 µm and spacing between turns as 1.5 µm with an area of 450×450 µm. The structure of L-1, the air-core spiral inductor is shown in Fig. 1. It is made of a pair of spirals which are inter-wound and fabricated on different metal layers (M3 and M4) with an air-bridge, resulting in increased current capacity and a decreased series resistance.

Due to the distance between the turns, capacitance present between the adjacent turns is minimized. The spiral inductor center trap is connected to the remaining part of the circuit by the air-bridge. Fig. 2 shows the equivalent model of L-1.

![Fig. 1 Layout of L-1.](image1)

![Fig. 2 Equivalent model of air-core inductor](image2)

B. Ferrite core inductor

The structure of the proposed ferrite integrated inductor(L-2) is shown in Fig. 3. The addition of the ferrite material in the core improves mobility and self resonant frequency of the spiral on-chip inductor[10,11] as compared to air core inductor. The depth of the ferrite filling is designed to be along the boundary of the spiral inductor in such a way that a closed magnetic circuit is formed. The properties of the materials used in the magnetic core mostly governs the performance of an inductor. For minimising the magnetic losses, the ferrite material selected in this work has a resistivity and permeability of 10 k - cm and 1000 respectively.
The inductance value of L-2 in the design is related to the ferrite permeability as follows:

\[ L = L_{air} + \frac{n_0 \mu_0 \mu_r}{2(1 + \pi \mu_r \mu_0 - 1)} \cdot \frac{w \cdot l}{t + \delta_f} \]  

(2)

where \( L_{air} \) is the inductance due to the air core, and the second term is the increase in inductance due to the addition of ferrite which is dependent on the permeability \( \mu_r \) of the ferrite. \( n_0 \) is the permeability of air, \( w, l \) and \( t \) are the width, length and ferrite film thickness respectively. \( \delta_f \) is the demagnetization factor which depends on the patterning of ferrite film.

In a similar manner, the quality factor is improved by:

\[ Q = \frac{\omega L}{R} = \frac{n_0 L_{mag}}{R_{mag} + \pi \mu_0 \mu_r} \]  

(3)

where \( R_{mag} \) results from the magnetic loss tangent (tan \( \delta_r \)) of the ferrite. For high resistivity ferrites, hysteresis and eddy current losses are negligible [12]-[15]. This results in a low loss tangent and low \( R_{mag} \) as \( R_{mag} \alpha \pi \mu_0 \). This improves Q-factor of L-2 compared to L-1 in the proposed work. L-2 has the same geometry as that of L-1 except for the ferrite film and has better Q and L value of 9.07 and 3.87 nH respectively.

The Q-factor and inductance of the spiral inductor depend on the geometrical aspects and frequency. It is known that geometrical aspects include the number of turns, ring shapes, the width of the spiral, the spacing between adjacent turns of the spiral, and its inner diameter. The pitfalls of the previous optimizations [7, 8] which aimed to improve Q-factor was that variables were analysed simultaneously rather than a single variable at a time. In the proposed work, effect on Q-factor and L-density of L-2 for varying inner diameters, line widths, ferrite permeability and substrate conductivity were analysed, considering one variable at a time. In addition, thickness of the ferrite material was varied to study its effect on Q-factor.

C. Ferrite core inductor with field shield substrate layer

In this work, the inductor L-3 is designed with a ferrite core on a three layered substrate. The free background carrier concentration is low in high resistivity Si substrates [16]–[18]. In [19], a physical model for inductor was developed incorporating substrate losses. Related work [20] involved vertical self-assembly of spiral inductors to reduce substrate losses but integration became all the more complicated.

Moreover, the use of high resistivity non-Si substrates results in non-uniform thermal expansion and led to device failure. Hence in the proposed L-3, the top layer substrate has low conductivity of 1 S/m (highest resistivity), followed by the field shield layer with conductivity of 2.5 S/m (moderate resistivity) and bottom layer with a higher conductivity of 5 S/m (lowest resistivity). The increase in conductivity from top to bottom minimizes the substrate losses as the field shield layer isolates the lower layer substrate from the inductor. Thus, the proposed L-3 intend to possess lower conductor and substrate losses.

Fig. 4(a) shows the circuit model of the inductor L-3. The parameters introduced by the addition of ferrite material and the field shield layer are the following: the real part of permeability introduces \( L_0 \) to \( L_s \), the imaginary part of permeability introduces \( R_1 \) to \( R_s \), due to the addition of ferrite. \( C_{e,AG} \) is the series capacitance added to \( C_s \), \( C_{s,1} \) is the capacitance added between inductor coils, \( C_{s,2} \) and \( C_{s,3} \) are the series and shunt capacitances respectively to \( C_{sub} \). The substrate resistance of the three layered structure is represented by \( R_1 \), \( R_{sub,1} \) and \( R_0 \). The substrate capacitance for top, field shield and bottom layer \( C_{sub,1} \), \( C_{sub,2} \) and \( C_{sub,3} \) respectively. The substrate resistance and capacitance of each layer are connected in parallel. The layout of the proposed inductor is designed and shown in Fig. 4(b). The Q and L values of L-3 is observed to be 10.54 and 3.76 nH and 10.54 respectively and found to be better than L-2.
Considering the effect of substrate losses, the Q-factor for L-3 can be expressed as:

\[ Q = \frac{\omega L}{R_{eq}} \times SRF \times SLF \]  

where the self resonance factor (SRF) of L-3 is given by:

\[ SRF = 1 - \frac{\omega L}{L_3} \left( C_0 + C_{t-shield} + C_{sub} \right) - \omega^2 L_3 \left( C_0 + C_{t-shield} + C_{sub} \right) \]  

The substrate loss factor (SLF) of L-3 is expressed as:

\[ SLF = \frac{1}{1 + \frac{\omega L}{L_3} R_{eq} \left( C_0 + C_{t-shield} + C_{sub} \right) \frac{1}{1 - \omega^2 L_3} \left( C_0 + C_{t-shield} + C_{sub} \right)} \]  

where \( R_{eq} \) is the effective resistance of each layer [21]. As seen from the eqns. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively. As seen from the eqn. (7-9), the top layer with thickness \( t_1 \) and field shield layer with thickness \( t_f \) has the contributions of resistances in top, field shield and substrate layers respectively.

Hence the Q-factor of L-4 is higher than L-3. The electric field strength in the substrate of L-3 and L-4 is shown in Fig. 5(a) and Fig. 5(b). The Q and L values and the average value of electric field strength in the substrate layers of L-3 and L-4 are shown in Table I.

As seen from the Table I, the average electric field penetration in substrate of L-3 is \( 1.215 \times 10^3 \) V/m as compared to \( 5.79 \times 10^3 \) V/m in L-4 and this is due to the presence of field shield layer in L-3. This implies that the substrate losses in L-3 is lesser than that of L-4 due to the presence of field shield layer. Section III deals with the integration of the proposed inductors L-1, L-2, L-3 and L-4 in the design of VCO.

### III. VCO DESIGN USING INDUCTOR DESIGN

The inductor design and its optimization are followed by the design of 65 nm CMOS based current reuse LC-VCO operating in the UWB band. The main VCO parameters are phase noise, power and frequency tuning range and these affect the FOM. In this work, four VCO circuits (VCO-1, VCO-2, VCO-3 and VCO-4) are designed, with same schematic, but utilising the four proposed inductors (i.e., L-1, L-2, L-3 and L-4). For accurate evaluation of effect of magnetic enhancement in inductors, they have the same spiral

<table>
<thead>
<tr>
<th>Inductor</th>
<th>L(nH)</th>
<th>Q</th>
<th>Electric field strength(V/m)</th>
<th>Average electric field strength (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-3</td>
<td>3.76</td>
<td>10.54</td>
<td>9.95 \times 10^3</td>
<td>3.76 \times 10^3</td>
</tr>
<tr>
<td>L-4</td>
<td>3.74</td>
<td>12.39</td>
<td>11.44 \times 10^3</td>
<td>5.79 \times 10^3</td>
</tr>
</tbody>
</table>
width, spacing between turns, and metal stack. The air-core inductor (L-1) is used in VCO-1, VCO-2 utilizes the ferrite-core inductor (L-2), VCO-3 utilizes the magnetic cored inductor, L-3 designed on a three layered substrate using field shield layer as intermediate layer and VCO-4 utilizes L-4. A negative-resistance LC-VCO topology is shown in the Fig. 6 with an LC tank (L,M₁ and M₂) where the proposed inductor designs forms L and cross coupled NMOS transistor pairs as driver (M₁ and M₃) and PMOS as load (M₂ and M₄). In the tank circuit, varactor (M₁ and M₂) forms C, which are used for frequency tuning. The varactors M₁ and M₂ are modeled by connecting the drain and source of the NMOS transistor together to act as one terminal and the other terminal is the gate. PMOS is used due to its low flicker noise. Both the load and driver have the same current flowing through them and offers the negative resistance necessary to compensate for the losses in the tank. For the purpose of reducing power, current reuse topology is widely used in RF circuits [22–23]. The switching transistors are cross connected thus resulting in the reuse of dc bias current as during the first half cycle of the output, the combination of PMOS (M₃) and NMOS (M₄) are in triode region and acts like a closed switch thus charging up the varactor in the tank. During the next half cycle, M₂ and M₃ are open and the tank discharges through M₄ and M₅. Thus, the current is drawn from the supply only for one half cycle, and in the next half cycle output signal is continued by the discharge current from the tank. Hence, the power dissipation of the circuit is reduced by current reuse. The frequency tuning of VCO is achieved with the help of varactor in the tank as it offers variable capacitance when the control voltage (V_c) applied to the gate of the varactor is varied. The frequency tuning range is further improved by using a switched capacitor array as shown by C₁ and C₂. Due to limited tuning capacity of NMOS varactors, in-built varactors are preferred. This VCO topology is integrated with the proposed spiral inductor structure (L) and performance parameters of VCO such as phase noise, power consumption, frequency tuning range and FOM are analysed. The loss resistance R_p of the LC tank circuit shown in Fig.7 is given by the equation

$$R_p = Q_p \sqrt{2}$$

where Q_p is the quality factor of the tank. R_p will be high when Q_p is maximum. R_L is the negative resistance offered by the MOS transistor pairs and should balance the losses in the tank to sustain oscillations. Q_L is given by:

$$Q_L = \frac{1}{\sigma R + \frac{1}{C}}$$

where Q_L = a_o L/R and Q_c = 1/CR_o. Q_c of varactors is generally high and can be neglected which means Q_L = Q_p. The Q-factor of a conventional spiral inductor is usually limited by its conductor and substrate losses. Hence it is inherent that designing an inductor with high L-density and Q-factor is crucial to maximize Q_p. Thus, the design of high Q-factor inductor is important in the design of VCO. Moreover, the startup condition for oscillation in a negative-resistance VCO is given by:

$$\frac{2}{\sqrt{V_{CC}}} = \frac{1}{i_p}$$

where \(i_p\) is the transconductance of the transistors driving the tank. \(V_{CC}\) is the oscillating signal amplitude of the VCO, and \(i_p\) is the offset current. The FOM of the VCO is given by:

$$\text{FOM} = 10 \log \left( \frac{\frac{F}{P_{diff}} \cdot \frac{20}{10}}{\frac{Q_o}{20}} \right)$$

where \(P_{diff}\) is the power dissipation of the VCO.

**IV. MEASUREMENTS AND DISCUSSIONS**

The four inductors are designed in HFSS and comprehensive simulations are carried out to determine the inductance and quality factor. Q-factor is varied by varying the properties of the core such as its permeability or by varying the dimensions of the core such as the thickness of ferrite filling and that of...
the conductor like its inner diameter, width or by varying the properties of the substrate such as its conductivity.

At low frequency, due to low inductive impedance and high capacitive impedance, the RF signal almost entirely takes the path through the spiral metal coil. With increase in frequency, Q grows initially and reaches $Q_{\text{max}}$. At frequencies beyond that of $f(Q_{\text{max}})$, inductive impedance is larger than capacitive impedance of the oxide and the impedance of the substrate. So, the larger part of the RF signal mainly passes through the substrate, forcing $Q$ to decay with frequency. The $Q$-factor of $L_1$, $L_2$, $L_3$ and $L_4$ is depicted in Fig.8. $L_2$, $L_3$ and $L_4$ exhibit an increase in $Q$-factor as compared to $L_1$.

In [24], the factors which influenced L-density and $Q$-factor are analyzed for an air-core inductor. In this work the effect of the factors, such as properties of the core, geometry of conductor and core and properties of the substrate, on ferrite integrated inductor, $L_2$, is taken of interest and are analyzed.

The properties of the core such as its permeability is varied for $L_2$ and its corresponding results are presented in Fig.9. The permeability of the ferrite is varied from 1050 to 1300, and an increase in peak $Q$-factor is observed i.e from 7.5 to 7.9 with increase in permeability. This stems from the fact that the magnetic losses are decreased with increase in core permeability.

Next in geometrical perspective, the thickness of the ferrite film and that of the conductor such as its inner diameter and width in $L_2$ are varied and its corresponding $Q$-factors have been observed. When the thickness of ferrite film is varied from 0.9 µm to 2 µm as in Fig.10, it is seen that the peak $Q$-factor increases from 7.4 to 7.9. This occurs because as the thickness increases, the ferrite filling encloses the inductor in such a way that the magnetic losses are minimum. But this increase in peak $Q$-factor reaches saturation after an optimum thickness of 2 µm as further reduction in losses does not occur. In terms of conductor, with the increase in the inner diameter from 119 µm to 136.5 µm as in Fig.11, the peak $Q$ value also increases from 7 to 9.2. This is because a larger inner diameter increases the total length of coil causing increase in skin depth $\delta$, which decreases series resistance and hence allowing more magnetic flux to flow through it. The $Q$-factor at high frequencies is improved with increase in inner diameter. It is insensitive to inner diameter at low frequencies, because at these frequencies, the $Q$-factor is dictated by the resistive loss. As observed in Fig.12, $Q$ factor was found to increase with increase in width of the spiral. As the width of coils increases from 13 µm to 15 µm, the area of magnetic flux increases hence increasing the peak $Q$-factor from 7.6 to 9.2. As the series resistance decreases with increase in metal line width, $Q$-factor increases at low frequency. As the operating frequency increases, eddy currents are produced in the coils and are accumulated at the edges of the strips, consequently decreasing the $Q$ factor at high frequencies.

Next moving to substrate properties, $Q$-factor of $L_2$ is analyzed by varying the substrate conductivity as in Fig.13. With decrease in conductivity of the substrate, the electromagnetic coupling between the substrate and inductor is reduced due to decrease in free carrier concentration in the substrate. This results in an improvement in peak $Q$-factor from 8.2 to 10.4 as the substrate conductivity varies from 5 S/m to 0.0001 S/m. It is observed that the improvement in $Q$-factor with decrease in conductivity saturates after 0.01 S/m.
In the above analysis, the optimum quality factor for the inductor $L_2$ is observed as 9.07 between (2-5) GHz. Similar analysis has been carried out for $L_1$, $L_3$ and $L_4$ and their optimum $L$-density and $Q$-factor are measured and mentioned in section II. The next parameter chosen is $L$-density which can be improved by enhancement of the magnetic properties of the core, determination of the optimal geometrical variables of the conductor and by isolation of the substrate. The $L$ value of proposed inductors depends on its operation frequency as:

$$L = \frac{1}{\omega} \ln\left(\frac{N}{n}\right)$$  \hspace{1cm} (15)

Thus at low frequencies $(\omega)$, $L$ value tends to be high and it gradually decreases to a constant value in the operating frequency range and slightly increases at higher frequencies. The variation of $L_1$, $L_2$, $L_3$, and $L_4$ with respect to frequency are as shown in Fig.14. The increase in $L$-density of $L_2$, $L_3$, and $L_4$ due to the ferrite filling.

The inductance structure of interest $L_2$, is analysed by varying the permeability of the ferrite filling as in Fig.15. The $L$-density was found to increase with the addition of ferrite filling as inductance is dependent on core permeability stated in eq.(1). Thus, as mentioned in section II, a better $L$-density of 3.87 nH is obtained for the ferrite core inductor, $L_2$ as compared to 2.11 nH of air-core inductor, $L_1$. Further, when the permeability of the ferrite material is increased, only a small improvement in inductance is observed. The inductance of the coil was observed to remain constant at around 3.9 nH in the frequency range of (2-7) GHz.

In geometrical view, for $L_2$, with the increase in the inner diameter from 119 $\mu$m to 136.5 $\mu$m, inductance also increases from 3.75 nH to 3.87 nH as observed in Fig. 16. The inductance value was found to remain constant for (2-7) GHz when the inner diameter is constant. Next, varying the inductor line width of $L_2$ from 13 $\mu$m to 15 $\mu$m causes a slight change in inductance from 3.75 nH to 3.9 nH as given in Fig.17. For a particular width, the inductance value was found to remain constant for (2-7) GHz.

Next moving to the substrate properties, inductance of $L_2$ is analysed by varying conductivity of substrate from 5 S/m to...
0.0001 S/m as in Fig. 18, the L value increased from 3.7 nH to 3.9 nH. The L value continued to remain constant in the (2-5) GHz range at around 3.8 nH when the conductivity is constant.

Based on the analysis, the optimum value of L-density of L-2 is found to be 3.87 nH. Based on similar analysis, optimum values of L-density for L-1, L-3 and L-4 are obtained and have been mentioned in section II.
The inductor optimization and analysis are followed by the simulation of VCOs designed in 65 nm CMOS using current reuse LC structure incorporating the proposed inductors [L-1, L-2, L-3 and L-4]. The corresponding VCOs are termed as VCO-1, VCO-2, VCO-3 and VCO-4 respectively. PSS and PNOISE analysis available in ADE-L window of Cadence Virtuoso are used to measure the phase noise of VCO.

Fig. 19 shows the measured phase noise for the four VCOs when the tuning voltage is varied from 0.1 to 1 V ($V_{ctrl}$). The purpose of this work is to focus on the merits and feasibility of utilizing the ferrite-cored inductor in the design of VCO. Hence, the frequency tuning overlap, which exists in the conventional VCO designs, is not taken into account. The comparison of performance of the VCOs is given in Table II. The phase noise for VCO-1 are observed to be -114.6 dBc/Hz, -134.2 dBc/Hz and -142.22 dBc/Hz at 1 MHz, 5 MHz and 10 MHz offset respectively. Similarly, the phase noise for VCO-2, VCO-3 and VCO-4 are found to be -113.05 dBc/Hz, -132.37 dBc/Hz and -140.13 dBc/Hz, -115.96 dBc/Hz, -135.01 dBc/Hz and -142.66 dBc/Hz, and -101.83 dBc/Hz, -121.27 dBc/Hz and -129.14 dBc/Hz at 1MHz, 5MHz and 10 MHz offset respectively.

Comparing the phase noise among the designed VCOs, at 1 MHz, VCO-3 shows better result, that is, -115.96 dBc/Hz and similarly it gives the best performance at 5 MHz and at 10 MHz, as -135.01 and -142.66 dBc/Hz. So the ferrite core inductor using field shield layered inductor design (L-3) is more suitable for VCO design. From Table II, it is observed that VCO-1 using air-core inductor L-1 shows better phase noise reduction than ferrite core inductor L-2 but at an expense of power. In case of the negative-resistance driver pairs ($M_2$, $M_3$, and $M_4$), $g_m$ required to start up the oscillation in the LCO is low while using ferrite integrated inductor because the Q-factor of $L-2$ and $L-3$ is greater than that of $L-1$. This reduction in $g_m$ lowers the power consumption of VCO, as validated in measurement, i.e. 3.3 mW for VCO-1, 2.64 mW for VCO-2 and 2.85 mW for VCO-3 at a 1.1 V supply. Also, the phase noise variation over the frequency range (1-10MHz) is lesser for VCO-2 (27.08 dB), VCO-3 (26.7 dB) and VCO-4 (27.01 dB) as compared to VCO-1(27.62 dB). Overall, VCO-3 with L-3 shows better phase noise reduction and lesser phase noise variation than others due to improvement in Q-factor via magnetic enhancement and field shield layer. Power consumption of VCO-3 is slightly greater than VCO-2 and VCO-4 but lesser than that of VCO-1. The FOM for VCO-1 is measured to be 177.7 dBc/Hz and VCO-2 is 177.1 dBc/Hz. VCO-3 has an FOM of 179.1 dBc/Hz and FOM of VCO-4 is 170.2 dBc/Hz.

V. CONCLUSION

In order to cater to the necessary requirements of high performance VCOs in RF-ICs, we have proposed an optimized the on-chip spiral inductor that gives better Q-factor by the introduction of field shield layer in between a high resistivity and low resistivity substrate. The study focuses on various factors affecting the Q-factor - magnetic properties of the core, dimensions of the spiral, and properties of the substrate. With the magnetic enhancement of the core and field shield substrate layer, Q-factor is improved by 53.8% and L-density of the proposed inductor is improved by 78.1% when compared to air-core inductor. The power consumption of the VCO-3 with proposed inductor (L-3) is observed to be 2.85 mW at a 1.1 V supply and it exhibits a noticeable better phase noise of -142.66 dBc/Hz at 10 MHz offset.

REFERENCES


TABLE II

<table>
<thead>
<tr>
<th>VCO</th>
<th>Frequency (GHz)</th>
<th>PN @1MHz (dBc/Hz)</th>
<th>Power (mW)</th>
<th>Q</th>
<th>L  (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCO-1</td>
<td>2.25-2.82</td>
<td>-114.6, -134.2, -142.22</td>
<td>3.30</td>
<td>6.85</td>
<td>2.11</td>
</tr>
<tr>
<td>VCO-2</td>
<td>2.04-2.88</td>
<td>-113.05, -132.37, -140.13</td>
<td>2.64</td>
<td>9.07</td>
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<td>VCO-3</td>
<td>2.27-2.79</td>
<td>-115.96, -135.01, -142.66</td>
<td>2.85</td>
<td>10.54</td>
<td>3.76</td>
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<td>VCO-4</td>
<td>2.34-2.76</td>
<td>-101.83, -121.27, -129.14</td>
<td>2.65</td>
<td>12.39</td>
<td>3.74</td>
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</table>

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