A Low-Voltage High-Frequency CMOS LC-VCO
Using a Transformer Feedback

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Abstract — The paper describes a 0.18-μm CMOS 8.5-GHz LC-tank VCO using a technique of reducing parasitic capacitances. Compared to the traditional crossed coupled method with more parasitic capacitances, in this work a symmetry transformer introduced by a transformer on feedback currents from the active components is employed to reduce parasitic capacitances in the VCO. The proposed oscillator can easily arrive at the requirement for high-frequency operation with the tuning range of 8.32 to 8.75 GHz (5%) at 0.7 V supply. With operating at 8.5-GHz frequency, the measured phase noise is -121.6 dBc/Hz at 1-MHz offset under the power dissipation of 6 mW.

I. INTRODUCTION

LC-tank voltage-controlled oscillators (VCOs) are widely used in RF communication systems, particularly in applications of phase-locked loops (PLLs). The performance of LC-based oscillators heavily depends on the quality of inductors and capacitors. A general oscillation frequency of LC topologies is equal to

\[ f_{osc} = \frac{1}{2\pi \sqrt{LC}} \]

suggesting that only the inductor and capacitor values can be varied to tune the frequency. Since it is difficult to vary the value of monolithic inductors, we simply change the tank capacitance to tune the oscillator. Thus, the resonant capacitances of the LC tank can be simplified to be regarded as the sum of constant capacitances and tunable ones. The former are mainly made of the parasitic capacitances of the inductor, the varactor and the transistors, and further limit the tuning range even reduce the operation frequencies because they cannot be varied by the control voltage. It’s interesting to note that to maximize the tuning range, operating frequencies and constant capacitances, the

a negative resistance to compensate the parasitic parallel resistance of LC tank for oscillation to occur. The capacitances of the tank can be formed from an effective parasitic capacitor \((C_p)\) and a varactor. The frequency-tuning varactor is represented as a voltage-controlled variable capacitor \((C_v)\) in shunt with a non-variable capacitor \((C_0)\).

With the transistor dimensions and tank inductance value known, the capacitance in the varactor can be calculated. Since:

\[ \omega_{osc} = \frac{1}{\sqrt{L \times C_{toto}}} \]

and all contributions to \(C_{toto}\) can be identify as:

\[ C_{toto} = (C_{GD} + C_{DB} + 4C_{GD} + C_0 + C_f) + C_f \]

if follows that

\[ C_f = \frac{1}{\omega_{osc} \times L} \times (C_{GD} + C_{DB} + 4C_{GD} + C_0) - C_p \]

Thus, the resonant capacitances of the LC tank can be simplified to be regarded as the sum of constant capacitances and tunable ones. These issues reveals an important drawback of LC oscillators: the former are mainly made of the parasitic capacitances of the inductor, the varactor and the transistors, and further limit the tuning range even reduce the operation frequencies because they cannot be varied by the control voltage. It’s interesting to note that to maximize the tuning range, operating frequencies and constant capacitances, the
Fig. 2 The proposed LC-VCO with transformer based inductors

canstant part in the tank must be minimized. However, it nevertheless suffers from a trade-off between the dynamic range and the operating frequency. The parasitic capacitances from the transistors and varactor constitute a significant fraction of the overall capacitance, thereby limiting tuning range [1].

B. Proposed LC-VCO Using a Transformer Based Inductor

To exclude the effective parasitic capacitor, an LC-based oscillator scheme with a symmetry transformer-based inductor is shown in Fig. 2. The symmetry transformer is placed between the gate and drain of M₁, the circuit with a feedback loop to oscillate. In order to reduce the required supply voltage and to eliminate additional noise contribution, the tail current in a conventional cross-coupled VCO is replaced by a system inductor \( L_{5-6} \). The LC oscillation scheme formed by inductor, the varactor and the transistors but without effective parasitic capacitor \( (C_P) \). The total capacitance seen from X to ground is equal to \( C_{toto} \) plus the Miller multiplication of \( C_{GS} + C_{DB} + 2C_{GD} + C_0 + C_I \), assumed \( A_r = -1 \). Now the varactor capacitance can be calculated. All contributions to \( C_{toto} \) are identified as:

\[
C_{toto} = C_{GS} + C_{DB} + 2C_{GD} + C_0 + C_I \quad (4)
\]

If follows that

\[
C_I = \frac{1}{\omega_m \times L} \left[ C_{DB} + 2C_{GD} + C_0 + C_{GS} \right] \quad (5)
\]

As expected, total capacitance \( (C_{toto}) \) in (2) is reduced to (4) for proposed LC-VCO. The resonant circuit is generally the type of parallel LC-tank, which is formed by the equivalent inductance from the primary coil of the transformer and the parasitic capacitances across the ports.

III. SIMPLIFIED LINEAR ANALYSIS

We exploit the LC oscillation scheme of Fig. 3 to construct the equivalent circuit shown in Fig. 2. It is composed of three mutual inductors \( L_1-L_6 \) [5], a MOS transistor pair. The inductors possess the coupling factor \( K \) and coupling polarity is assigned by the dot convention in the figure. The LC oscillation operation can be explained by considering the half-circuit model of Fig. 4. In the figure, \( R_1 \) and \( L_1 \) represent the series resistance and inductance of the primary coil respectively while \( R_2 \) and \( L_2 \) represents that of the secondary coil; \( C \) is the effective tank capacitance. In this work, a symmetric structure of the transformer is adopted, thereby \( L_1 = L_2 = L \), and \( R_1 = R_2 = R_1 = R \). By considering the resonator core’s loop in Fig. 4, we have

\[
(sL + R)\times i_1 - i_2\times sKL + i_2\times \frac{1}{sC} = 0 \quad (6)
\]

\[
i_1 = g_m\times v_{gs} \quad (7)
\]

\[
v_s = -i_2\times \frac{1}{sC} \quad (8)
\]
Substituting \( s = j\omega \) from above equations, we can get

\[
iz\left( R - \frac{g_{m}KL}{1 + g_{m}R_s}C \right) + j\omega \left( L - \frac{1}{\omega^2C} \right) = 0
\]  \hspace{1cm} (9)

Imaginary parts of the denominator must drop to zero when oscillation occurs, and we have

\[
\omega_{osc}^2 = \frac{1}{LC}
\]  \hspace{1cm} (10)

The oscillation frequency obviously depends on the inductances and capacitances of the tank. In addition, oscillate loss through the serial resistance \( R \) will be cancelled while oscillating. By equations (9) and (10), the transconductance must satisfy the following condition for a sustained oscillation:

\[
\frac{g_{m}KL}{1 + g_{m}R_s}C \geq R
\]  \hspace{1cm} (11)

and we get

\[
g_{m} \geq \frac{RC}{KL - RCR_s}
\]  \hspace{1cm} (12)

IV. MEASUREMENT RESULTS

To verify the performance of the LC-VCO as previously described, the proposed circuits were fabricated in 0.18-\( \mu \)m CMOS technology. Fig. 5 shows
the microphotograph of the test chip with an area of 830×910 μm² including the output buffers and I/O pads. Each output signal is connected to an open-drain circuit with an externally match resistance of 50 Ω. The VCO was tested on an FR-4 PC board using Agilent E4407B Spectrum analyzer for measurement. With a 0.7-V supply, it consumes the power of 6 mW. Fig. 6 shows the measured phase noise at 1-MHz offset. The measured frequency tuning characteristic is shown in Fig. 7. As can be seen, the tuning range is 5% (8.32 to 8.75 GHz). The VCO was tested on an FR-4 PC board using Agilent E4407B Spectrum analyzer for measurement. With a 0.7-V supply, it consumes the power of 6 mW. Fig. 6 shows the measured phase noise at 1-MHz offset. The measured frequency tuning characteristic is shown in Fig. 7. As can be seen, the tuning range is 5% (8.32 to 8.75 GHz). The measured spectrum of 8.5 GHz is shown in Fig. 8, and they prove that the resonant oscillation of the LC-tank merely occurs in the primary of the transformers. Fig. 9 shows a plot of the measured phase noise of the 8.5-GHz output is -121.5dBc at 1-MHz offset.

A widely accepted figure of merit (FoM) for VCOs is given by [6]:

\[
    FoM = PN(\Delta f) - 20 \log \left( \frac{f_0}{\Delta f} \right) + 10 \log \left( \frac{P_{\text{out}}}{1\text{mW}} \right) \tag{13}
\]

The FoM normalizes the phase noise at a given offset \( \Delta f \), the center frequency \( f_0 \), and the power consumption \( P_{\text{out}} \) in milliwatts. The best FoM of the VCO is -190 dBc/Hz. Table 1 shows the FoM of several comparable under around 1-V supply over the past years [7]-[10].

V. CONCLUSION

A high frequency and low voltage LC-VCO was achieved by using a symmetric transformer-based inductor. It is an interesting work covering the use of Miller multiplication to reduce parasitic capacitances, for building high-frequency VCOs. The prototype LC-VCO can extend the operating frequencies at 8.32 to 8.75 GHz in a standard 0.18-μm CMOS process at minimum operating supply voltages of 0.7 V. The measured results demonstrate the functionality of the LC-VCOs with the proposed to reduce parasitic capacitances technique.

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REFERENCES


Table 1  Comparison of performance with prior works

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<td>0.18 CMOS</td>
<td>8.5</td>
<td>0.4</td>
<td>0.7</td>
<td>6</td>
<td>-121.6 @ 1MHz</td>
<td>-190</td>
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<td>[7]</td>
<td>0.18 CMOS</td>
<td>2.4</td>
<td>4.4</td>
<td>1</td>
<td>2.6</td>
<td>-116.8 @ 1MHz</td>
<td>-180.25</td>
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<td>[8]</td>
<td>0.18 CMOS</td>
<td>5.8</td>
<td>0.198</td>
<td>0.8</td>
<td>-</td>
<td>-100 @ 500KHz</td>
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<td>[9]</td>
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<td>[10]</td>
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<td>4.8</td>
<td>0.4</td>
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