A 0.1-V 13-GHz Transformer-Based Quadrature VCO with a Capacitor Coupling Technique in 90nm CMOS
Tatsuya Kamimura, Sang_yeop Lee, Satoru Tanoi, Hiroyuki Ito, Noboru Ishihara and Kazuya Masu

Solutions Research Laboratory, Tokyo Institute of Technology
4259-S2-14 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan
Phone: +81-45-924-5031 E-mail: paper@lsi.pi.titech.ac.jp

1. Introduction
A low power RF circuit is strongly demanded by sensor and healthcare systems. High-microwave-band is attractive for such applications because antenna size can be easily reduced. This paper proposes a high-microwave-band quadrature VCO (QVCO) that operates under 0.1 V power supply to save power. The conventional VCO with current sources [1] is generally difficult to achieve enough negative conductance under low supply voltage. Thus, transformer feedback and body bias coupling techniques have been reported [2,3]. However, it is still a challenge to obtain sufficient transconductance $g_m$ at high-microwave band. The present work introduces the capacitor coupling technique to boost $g_m$ of the transformer feedback QVCO. The prototype QVCO is fabricated by using 90 nm Si CMOS technology, and measured performances are discussed.

2. Low-Supply-Voltage QVCO
Fig. 1 shows the proposed QVCO. Low power supply operation at high-microwave band is achieved by leveraging two techniques: transformer feedback and capacitor coupling.

It has been reported that a transformer feedback can enhance signal swing even though the cross-coupled transistors ($M_1$, $M_2$, $M_3$, and $M_4$) have low transconductance $g_m$ [2]. This work exploits it and introduces capacitor coupling technique for achieving quadrature operation and $g_m$ boosting at higher frequency operation. Signals at the drain terminals are injected to the source terminals through capacitors $C_s$. The injected signals on source terminals have 90 degree phase shift and are amplified by common-gate amplifier operation. Capacitors $C_s$ and resistors $R_g$ are used to feed gate bias voltage independently for low supply voltage operation.

The square-shaped spiral transformer as shown in Fig. 2 was designed. A top thick metal layer is used for achieving higher Q-factor. Table I shows simulated inductance ($L_p$, $L_s$), Q-factor ($Q_p$, $Q_s$) and coupling coefficient of the transformer $k$ at frequency of 13 GHz. Dimensions were optimized by using a 2.5D electro-magnetic-field analysis.

3. Measurement Results
Fig. 3 shows a chip micrograph of the proposed QVCO. The QVCO area is 800 um x 250 um including signal output buffers for testing. The measured frequency tuning ranges were 13.06-13.12 GHz and 13.17-13.22 GHz at power supply voltages of 0.1 V and 0.2 V, respectively, with $V_{bias} = 0.4$ V. The power consumption of the QVCO core were 0.68 mW and 2.8 mW, respectively, when the varactor control voltage was equal to the supply voltage ($V_{ctl} = V_{dd}$). Fig. 4 shows phase noise characteristics at $f_0 = 13$ GHz under free-running condition. Phase noises of the QVCO at 1 MHz offset were -94 dBc/Hz and -100 dBc/Hz at supply voltages of 0.1 V and 0.2 V, respectively. Fig. 5 shows frequency spectrum of the VCO output at $f_0 = 13$ GHz. Low carrier power with the high system noise is because of limited frequency range of test buffers.

Performances of the proposed QVCO are summarized in Table II with the previously reported VCOs. The proposed QVCO achieves high-frequency operation under 0.1V power supply. Power consumption is 0.68 mW and is comparable with other low-supply-voltage VCOs. A figure of merit $(FoM)$ on the phase noise $(L(\Delta f))$, the output frequency $(f_0)$, and the power consumption $(P_{diff})$ are also estimated. $FoM$ is expressed as

$$FoM = L(\Delta f) = 20 \log \left( \frac{f_0}{\Delta f} \right) + 10 \log \left( \frac{P_{diff}}{1mW} \right)$$

Measured $FoM$ values were -178 dBc/Hz with 0.1 V and 0.2 V power supply.

4. Conclusions
This paper proposed the transformer-feedback QVCO with capacitor coupling technique for boosting $g_m$ at high frequencies. The prototype QVCO in 90 nm Si CMOS achieved 13 GHz operation under low power supply voltage of 0.1 V with typical $FoM$.

Acknowledgements
This work was partially supported by MIC.SCOPE, KAKEN-HI and VDEC in collaboration with Agilent Technologies Japan, Ltd., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

References
Fig. 1 Proposed QVCO with the capacitor coupling.

Fig. 2 On-chip square-shaped spiral transformer.

Table I Transformer Parameters at 13 GHz.

<table>
<thead>
<tr>
<th>$L_p$</th>
<th>$Q_p$</th>
<th>$L_s$</th>
<th>$Q_s$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19 nH</td>
<td>17.9</td>
<td>0.14 nH</td>
<td>14.7</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table II Performance summary and comparison of LC-VCOs.

<table>
<thead>
<tr>
<th>CMOS process</th>
<th>$f_0$ [GHz]</th>
<th>$V_{dd}$ [V]</th>
<th>$P_{diff}$ [mW]</th>
<th>$\Delta f$ [MHz]</th>
<th>$L(\Delta f)$ [dBC/Hz]</th>
<th>$FoM$ [dBC/Hz]</th>
<th>Area [mm$^2$]</th>
<th>IQ Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>90 nm</td>
<td>13</td>
<td>0.1</td>
<td>0.68</td>
<td>-94</td>
<td>-178</td>
<td>0.20</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>13</td>
<td>0.2</td>
<td>2.80</td>
<td>-100</td>
<td>-178</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[1] 130 nm</td>
<td>10</td>
<td>1.8</td>
<td>N/A</td>
<td>1</td>
<td>-95</td>
<td>N/A</td>
<td>0.16</td>
<td>Yes</td>
</tr>
<tr>
<td>[2] 180 nm</td>
<td>1</td>
<td>0.4</td>
<td>1.46</td>
<td>1</td>
<td>-129</td>
<td>-190</td>
<td>0.76</td>
<td>No</td>
</tr>
<tr>
<td>[3] 90 nm</td>
<td>4</td>
<td>0.2</td>
<td>0.33</td>
<td>1</td>
<td>-113</td>
<td>-187</td>
<td>0.76</td>
<td>Yes</td>
</tr>
<tr>
<td>[4] 180 nm</td>
<td>10</td>
<td>1.0</td>
<td>10</td>
<td>1</td>
<td>-112</td>
<td>-182</td>
<td>0.88</td>
<td>Yes</td>
</tr>
</tbody>
</table>