A 0.8V 5.9GHz WIDE TUNING RANGE CMOS VCO USING INVERSION-MODE BANDSWITCHING VARACTORS

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Abstract—This paper presents a completely integrated 0.8V 5.9GHz CMOS voltage-controlled oscillator (VCO) with inversion-mode MOS (IMOS) bandswitching varactors. IMOS varactors are used to maintain a large tuning range when the supply voltage is lower than 1V. Moreover, a large resistance connects to the bulk of each IMOS varactor to further improve the VCO tuning capability. Through this large resistance, the tuning range increases by 500MHz. A bandswitching topology is used to ameliorate the adverse effects of highly sensitive IMOS varactors. The VCO was simulated with a 0.8V supply with a tuning range of 29.12% from 4.4 to 5.9 GHz when tuned from 0 to 0.8V. The simulated phase noise is -109.65dBc/Hz at 1MHz offset from the carrier frequency of 5.52GHz. The VCO-core power dissipation is 1.2mW. When the supply voltage is reduced to 0.6V, the tuning range of the VCO becomes 22.64% from 4.7 to 5.9GHz and the phase noise is -105.24dBc/Hz at 1MHz offset from the carrier at 5.65GHz. In this case, the VCO core consumes only 0.9mW. The VCO was implemented in TSMC 0.18-µm CMOS technology with deep n-well processing.

This paper is organized as follows. Section II describes the passive elements in the VCO circuit. Next, the IMOS varactors are introduced. Next, the bandswitching topology is introduced. Finally, the integrated spiral inductor model used in simulation is described. Section III describes the design of the proposed VCO. Section IV presents the simulation results. Finally, the conclusion is drawn in Section V.

I. INTRODUCTION

Due to the large parasitic capacitance of bulk CMOS technology, integrated LC oscillators suffer from a small frequency tuning range. This problem is even worse when the supply voltage is lowered due to technology scaling. Accumulation MOS (AMOS) varactors have been a popular choice when the tuning voltage is larger than 1V [1]-[4]. However, when the tuning voltage is lower than 1V, the accumulation MOS (AMOS) varactors cannot achieve their physical maximum and minimum capacitance. This will degrade the VCO tuning capability considerably.

To maintain a fine VCO tuning range in the case of low supply voltages, IMOS varactors are used in this VCO design because of their natural abrupt gradient of the C-V curve (capacitance relative to tuning voltage curve). To improve the tuning capability further, a large resistance connects to the bulk of each IMOS varactor to isolate the gate to bulk parasitic capacitance of IMOS from the oscillatory output port. The simulation results show that using the new modified IMOS structure, the effective minimal capacitance (C_min) is reduced from 775 to 590fF and the frequency tuning range increases by 500MHz. When the supply voltage is 0.8V, the tuning range of the VCO is 29.12% from 4.4 to 5.9GHz and the phase noise is -109.65dBc/Hz at 1MHz offset from the carrier at 5.52GHz. The VCO-core power dissipation is 1.2mW of power. When the supply voltage is reduced to 0.6V, the tuning range of the VCO becomes 22.64% from 4.7 to 5.9GHz and the phase noise is -105.24dBc/Hz at 1MHz offset from the carrier at 5.65GHz. In this case, the VCO core consumes only 0.9mW. The VCO was implemented in TSMC 0.18-µm CMOS technology with deep n-well processing.

II. THE PASSIVES

A. Inversion-mode MOS Varactors

Figure 1 shows the circuit schematic and equivalent models of the IMOS varactors used in the VCO design. A large poly resistance Rs connects the bulk of the NMOS and the ac ground terminal Vbias. When the terminal DS in Figure 1(a) is biased at the positive end voltage, the IMOS is operated in the depletion mode and Figure 1(b) shows the equivalent model. The conductance looking into terminal G in Figure 1(b) is

$$\frac{j \omega C_{\text{ox}} \parallel C_d}{j \omega C_{\text{ox}} \parallel C_d + G_s} + j \omega C_{\text{parasitic}}$$

(1)

where \(G_s\) is the inverse of the resistance of \(R_s\). If \(G_s\) is much smaller than \(\omega C_{\text{ox}}(C_d)\) and \(\omega C_{\text{parasitic}}\), the conductance looking into terminal G in Figure 1(b) is approximately equal to \(j \omega C_{\text{parasitic}}\) and the minimum capacitance \(C_{\text{min}}\) can be estimated by \(C_{\text{parasitic}}\). However, if the bulk is connected
directly to the ac ground (case of infinite $G_s$), $C_{\text{min}}$ will become $C_{\text{parasitic}} + C_{\text{ox}} || C_{\text{dep}}$. Thus, $C_{\text{min}}$ can be decreased by $C_{\text{ox}} || C_{\text{dep}}$ by using a large resistance $R_s$ in Figure 1(a). When $DS$ is biased at the negative end, a sheet of electrons accumulates at the surface of the channel and the IMOS is operated in the inversion mode. Figure 1(c) shows the equivalent model.

![Figure 1](image1)

**Figure 1.** (a) Circuit schematic of an IMOS varactor with a large bulk resistor $R_s$ (b) The equivalent model in depletion mode (c) The equivalent model in inversion mode

The HSPICE simulated C-V characteristics of an IMOS varactor are shown in Figure 2. The resistance of $R_s$ is set to 10k in this simulation. The voltage of terminal $G$ in Figure 1 is set to a fixed voltage, 0.8V, and the voltage of $DS$ is swept from 0 to 0.8V. The improvement of the $C_{\text{max}}/C_{\text{min}}$ ratio using the modified varactor of Figure 1(a) is close to 25%. It should be noted that the center voltage $V_c$ in Figure 2 can be right-shifted by increasing the bulk biased voltage, $V_{\text{bias}}$ in Figure 1. In the proposed VCO design, $V_{\text{bias}}$ is biased at 0.4V.

B. Bandswitching Varactors

Large varactor sensitivity $k_v$ degrades of phase noise performance $L(\Delta f, k_v)$. The effect of $k_v$ on phase noise can be shown by the following equation [1],

$$L(\Delta f, k_v) = 10 \log \left\{ \frac{f_o}{2Q\Delta f} \right\}^2 \left[ \frac{FkT}{2P_o} \left( 1 + \frac{f_o}{\Delta f} \right) + \frac{k_nv_o}{2kCL\Delta f} \right]^2, \quad (4)$$

where $f_o$ is the carrier frequency, $Q$ is the quality factor, $\Delta f$ is the offset frequency from the carrier, $F$ is the noise factor of the gain element, $k$ is Boltzmann’s constant, $T$ is the flicker noise corner frequency, and $k_{CL}$ is a function of $C$ and $L$ in the resonator. If the required tuning range is large, a bandswitching topology is suggested to reduce varactor sensitivity $k_v$ [1]. However, Figure 3 shows the C-V characteristics of an AMOS varactor with the same size and bias condition as the IMOS varactor simulated in Figure 2. AMOS cannot be fully switched when tuned from 0 to 0.8V. Thus, there is no benefit to implement bandswitching topology with AMOS varactors to reduce $k_v$ with low tuning voltage. On the other hand, from Figure 2, the gradient of the IMOS C-V curve is relatively small when the voltage of $DS$ is 0 or 0.8V. This means that $k_v$ is also relatively small at 0 and 0.8V. It makes sense using IMOS as on/off only varactors in a bandswitching topology to improve phase noise performance with low supply voltages.
C. Spiral Inductor

Figure 4 is the layout and equivalent model of the spiral inductor. The spiral inductor is implanted using the thick top metal and the inner radius is 80 $\mu$m. A symmetrical architecture with center tapping is used to save chip area. ADS Momentum is used for simulation. The two-turn inductor provides 1.55nH of inductance, and the quality factor is from 9.5 to 11 across the entire tuning range.

III. VCO DESIGN

The VCO was designed in TSMC 0.18$\mu$m CMOS technology. Figure 5 shows the circuit schematic for the VCO. It is an LC cross-coupled VCO with nMOS latch to generate negative resistance. The current source $I_{dc}$ draws 1.5mA. The bandswitching IMOS varactor array consists of one continuous tuning varactor controlled by tuning voltage $V_{c1}$ and two on/off only digital switching varactors controlled by $V_{c2}$ and $V_{c3}$. Gate terminals (G in Figure 1) of each IMOS connect to the oscillatory outputs ($V_{o+}$ and $V_{o-}$ in Figure 5) and the drain and source terminals (DS in Figure 1) connects to the tuning ports ($V_{c1}$ to $V_{c3}$ in Figure 5). The C-V curve of the three varactors on each side was shown in Figure 2.

IV. SIMULATION RESULTS

The VCO circuit in Figure 5 is simulated with a 0.8V supply. Figure 6 shows the tuning characteristics of the VCO when $V_{c1}$, $V_{c2}$, and $V_{c3}$ are connected together and tuned from 0 to 0.8V. From the simulation results shown in Figure 6, the frequency tuning range can be improved by 500MHz (50%, from 1 to 1.5GHz) through the large resistance $R_s$ connected to the IMOS bulk. Figure 7 shows the tuning range of the VCO with the bandswitching IMOS varactor array mentioned before. The carrier frequency can be tuned between 4.4 to 5.9GHz, achieving 29.12% tuning range with the center frequency at 5.15GHz. Figure 8 shows the phase noise simulation result when the VCO operates at a carrier frequency 5.52GHz. It has -88.01dBc/Hz at 100KHz offset and -109.65dBc/Hz at 1MHz offset. The phase noise is simulated when $V_{c1}$ is 0.3V and $V_{c2}$ and $V_{c3}$ are 0.8V. When the supply voltage is reduced to 0.6V, the tuning range becomes 22.64% from 4.7 to 5.9GHz. The phase noise is 81.52dBc/Hz at 100KHz offset and -105.24dBc/Hz at 1MHz offset from the carrier at 5.65GHz.
A widely used figure of merit (FOM) to make comparisons between different VCOs is defined as

\[
\text{FOM} = \frac{f_o}{\Delta f} - 20 \log \left( \frac{f_o}{\Delta f} \right) + 10 \log \left( \frac{P}{1\text{mW}} \right)
\]  \hspace{1cm} (5)

where \( f_o \) is the phase noise at \( \Delta f \) offset from the carrier at \( f_o \) and \( P \) is the power dissipation of the VCO-core. The FOM is this design is -183.65dBc/Hz at 5.52GHz at a 0.8V supply voltage. When the supply voltage is reduced to 0.6V, the FOM becomes -180.74dBc/Hz at 5.65GHz.

Table 1 summarizes the performance of the proposed VCO while Table 2 provides a comparison with some recently published VCOs. It can be seen that the proposed VCO has good tuning capability even if the tuned voltage is lower than 1V.

### V. CONCLUSION

A 0.8V 5.9GHz fully-integrated cross-coupled LC VCO is presented. IMOS varactors with large bulk resistance are used to achieve 29.12% frequency tuning range. To correct for the adverse effects of IMOS varactors caused by high sensitivity, the bandswitching topology is used. When the supply voltage is reduced to 0.6V, the proposed VCO still has 22.64% frequency tuning range. Therefore, the proposed IMOS varactors provide a solution to maintain the VCO frequency tuning capability when the supply voltage is lower than 1V.

### ACKNOWLEDGEMENT

C. Y. Yu would like to thank M. P. Houlgate, T. W. Yu, C. Y. Chou, S. Wang, and H. Y. Su for their advice and thank National Chip Implementation Center (CIC) for technical support.

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