

A linearized tuning varactor for voltage controlled oscillator

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Abstract: A linearized tuning varactor for the voltage controlled oscillator (VCO) is proposed in this paper. The capacitance-voltage (C-V) curve is linearized by combining an accumulation MOSFET (AMOS) and PMOS in parallel to form the varactor. Two ring voltage controlled oscillators (ring VCOs) are fabricated and measured with a standard 65-nm CMOS process. They are both identical except for the varactor. The first VCO uses the proposed varactor, and the second one is tuned by a conventional AMOS-only varactor for reference. The ring VCO with the proposed varactor operates from 500.5 to 807.6 MHz, and the VCO gain (K_{VCO}) varies from 183 to 284 MHz/V. Comparing the reference VCO with the AMOS-only varactor, the measured K_{VCO} variability is reduced by 82%. The phase noise is between -89 dBc/Hz and -92 dBc/Hz at 1 MHz offset while dissipating 0.8 mA from a 1.2-V supply.

Keywords: varactor, voltage controlled oscillator, linearized tuning gain

Classification: Integrated circuits

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1 Introduction

A linear VCO tuning gain (K_{VCO}) is preferred for the voltage controlled oscillator (VCOs) in PLLs, so that the PLL loop dynamics, such as settling time and phase margin, do not change with the control voltage. Generally, the methods to tune the frequency of the ring oscillator includes: varying the resistance of a linear MOSFET, varying the dc current or the supply voltage of oscillators, varying the output capacitance load [1]. For the current-tuning or resistance-tuning ring oscillator, a voltage-to-current (V/I) converter, such as a MOS current source, is often employed to transform the control voltage to dc current to tune the oscillation frequency. However, as the supply voltage shrinks, the input voltage range is limited by the threshold voltage of MOSFET, and the output current is sensitive to PVT variations. On the other head, the varactor-tuning ring-oscillator can achieve a wide control voltage range by changing the capacitive load of each delay cell of the ring oscillator even under a low supply voltage. However, the MOS varactor shows more non-linearity and a relatively narrow tuning range as the supply voltage and process scale down. Furthermore, the varactor’s nonlinear C-V characteristics increase the up-conversion of flicker noise to the VCO’s $1/\Delta f^3$ noise region [2]. The methods of reducing the nonlinearity of the varactor includes, combining a discrete digital-switching capacitor bank and MOS varactor for coarse and fine frequency tuning, which requires additional calibration time [2]; connecting a varactor bank with different bias voltage in parallel to get an equalized K_{VCO} , which needs an additional bias circuit [3, 4, 5]; adopting a new varactor device with the n-type and p-type mixed-doping gates with a special process [6, 7].

In this paper, a simple but efficient gain linearized varactor is proposed, consisting of the gate-bulk capacitance (C_{GB}) of an AMOS and PMOS. The PMOS is biased by a negative V_{SB} to broaden the depletion region and keep a monotonic function for C_{GB} . This paper is organized as follows. In Section 2, the proposed varactor topology is analyzed. Section 3 gives the experimental results. Finally, a conclusion is provided in Section 4.

2 The proposed combined AMOS and PMOS varactor

The proposed varactor structure is shown in Fig. 1, which is combined by an AMOS and PMOS varactor in parallel. The drain and source of the PMOS are connected together to the lowest dc-voltage in the circuit, and the tuning voltage V_{TUNE} is connected to its n-well bulk. The AMOS and the PMOS varactor both operate in depletion and accumulation mode.

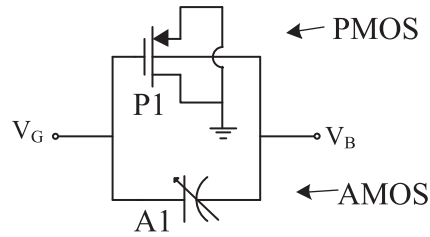


Fig. 1. The proposed AMOS and PMOS combined varactor

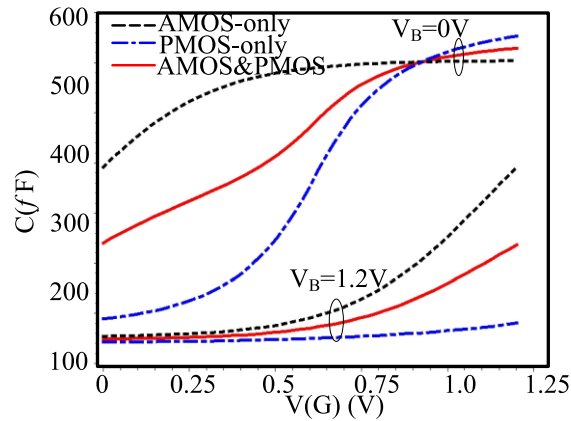


Fig. 2. The simulated C-V curves of different varactor

For a conventional AMOS varactor, when $V_{GB} > V_{FB}$, the MOS device enters the accumulation region, the gate-bulk capacitance C_{GB} gets closer to C_{OX} , and the C - V curves start to be flatten, as shown in Fig. 2, where V_{GB} is its gate-bulk voltage, V_{FB} is the flatband voltage, and C_{OX} is the gate-channel capacitance [8]. Since the steepness of the $C(V)$ curve generates the frequency/voltage gain (K_{VCO}) of VCOs, the K_{VCO} is greatly reduced in the low frequency band after $V_{GB} > V_{FB}$.

On the other hand, the PMOS biased in the inversion and depletion region, with its n-well being connected to V_{DD} , can also be used as a varactor. However, this inversion-mode varactor has a strong nonlinear tuning range. The flatband voltage of a MOS transistor V_{FB} can be written as [9]

$$V_{FB} = \phi_G - \phi_f \quad (1)$$

For the n-type poly gates $V_{FB} \approx -0.55 + \phi_f$, and for the p-type poly gates $V_{FB} \approx 0.55 + \phi_f$. Thus, as regards to the n-well beneath the gate, the flatband voltage is close to 0 V for n-type gates, and is shifted by approximately 1 V when using p doping for the MOS gates. The shift of the flatband voltage leads to an offset between the two varactors' C - V curves for the same bias voltage V_{GB} . Therefore, the AMOS and PMOS varactor can be combined in parallel to achieve an averaged capacitance, thus achieving a more linear C - V behavior than the AMOS-only varactor or PMOS-only varactor. The C-V curves of the AMOS-only varactor and the AMOS&PMOS varactor are simulated as shown in Fig. 2. When the bulk voltage approaches the supply voltage, the capacitance of the AMOS varactor is saturated; whereas the C - V curves of the AMOS and PMOS combined varactor still proportionally increase with the tuning voltage.

To achieve a monotonic C - V curve, the PMOS varactor should be biased in depletion and accumulation region across the voltage tuning range of V_G , similar to

an AMOS varactor. However, the traditional use of the PMOS varactor, where its gate is one terminal and the source, drain and bulk are tied together to form the other terminal, would make the PMOS enter the inversion mode when $V_{GB} < -|V_{TH}|$ [10]. For the proposed varactor, the drain and source of the PMOS are connected to the lowest DC voltage in this circuit (i.e., the *GND*), and the tuning voltage V_{TUNE} is connected to its n-well bulk as shown in Fig. 3(a). The substrate bias voltage V_{SB} is given by

$$V_{SB} = -V_{TUNE} \quad (2)$$

a negative substrate bias voltage V_{SB} is applied for the PMOS varactor. Therefore, the PMOS varactor does not enter the inversion region due to its body effect.

For the PMOS, an inversion channel with mobile holes builds up for $V_{GB} < -|V_{TH}|$, and the threshold voltage V_{TH} shifts depends on the negative substrate bias voltage V_{SB} as follows:

$$|V_{TH}| = |V_{T0}| + \gamma\sqrt{|2\phi_f + V_{SB}|} - \gamma\sqrt{|2\phi_f|} \quad (3)$$

where γ is the body-effect coefficient, V_{SB} is the substrate bias voltage, and ϕ_f is the bulk Fermi potential, the value V_{T0} is the threshold voltage at a substrate bias voltage of zero [10]. The shift of the PMOS V_{TH} from a negative substrate bias voltages V_{SB} enables the depletion region widen. From Fig. 3(b), when V_{SB} gets negative, the depletion region of the PMOS is broadening, and a monotonic C-V function for the PMOS varactor is obtained for a wide range of values of V_G .

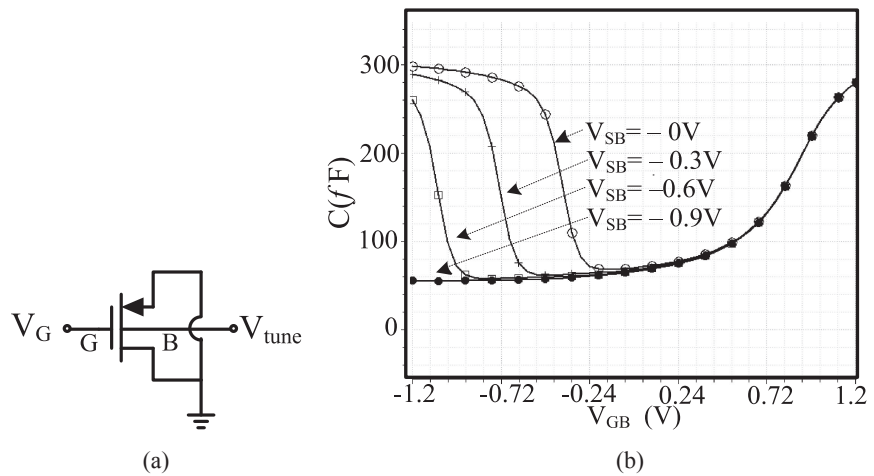


Fig. 3. (a) The proposed PMOS varactor circuit (b) Broadening of the PMOS varactor's depletion region by a negative V_{SB}

3 Measurement results

To validate the presented varactor structure, two ring VCOs with identical differential pair and bias current are fabricated with a standard 65 nm CMOS process as shown in Fig. 4. The chip photograph of the two VCO is shown in Fig. 5. The ring VCO consists of three differential delay cells. The first ring VCO is employed with the proposed PMOS and AMOS combined varactor, and for the second VCO for reference, the PMOS varactor is replaced with an AMOS varactor. The oscillation

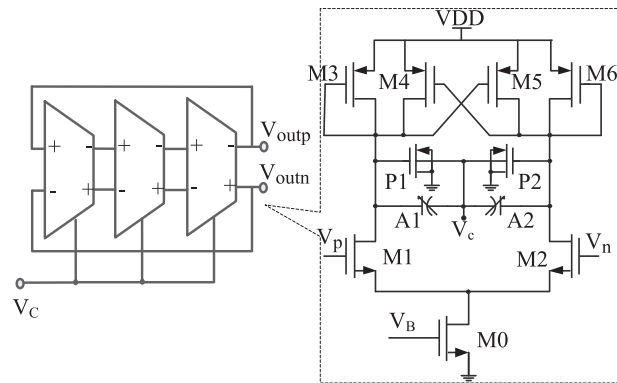


Fig. 4. Schematic of the ring VCO

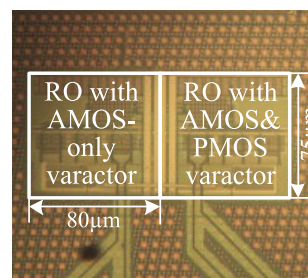


Fig. 5. Chip photograph

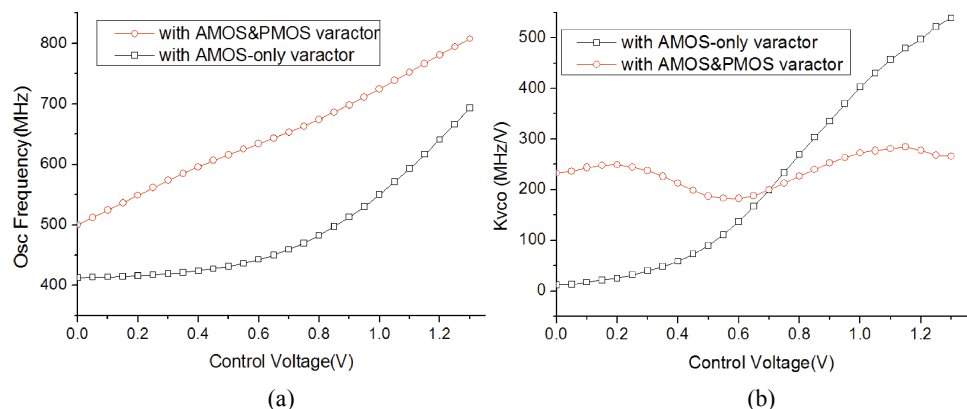


Fig. 6. (a) Measured frequency tuning of the ring VCO (b) Measured frequency tuning sensitivity (K_{VCO})

frequency $f_{\text{osc}} = 1/(3t_{\text{delay}}) = 1/(3RC_{\text{load}})$, where R , C_{load} are the output resistance and load capacitance of each delay cell. The C-V characteristics of the varactor can be revealed by the measurement of the ring VCO operating frequency.

The measured operating frequency at different tuning voltages is shown in Fig. 6(a). Each ring VCO dissipates 0.8 mA at a 1.2 V supply voltage. At a control voltage from 0 to 1.3 V, the oscillating frequency is tuned from 500.5 to 807.6 MHz. The ring VCO with the AMOS-only varactor for reference is measured from 412.7 to 691.1 MHz. Fig. 6(b) shows the measured tuning gain of the ring VCO. Around the tuning range, the gain of the ring VCO employing the AMOS and PMOS combined varactor varies from 183 to 284 MHz/V, whereas the gain of the reference VCO with the AMOS-only varactor varies from 12 to 501 MHz/V. As

shown in the previous analysis, for the AMOS-tuned VCO, the effective capacitance of the AMOS varactor is saturated in the low frequency band. The K_{VCO} variability of the combined AMOS&PMOS varactor is reduced by 82% compared with the VCOs tuned by AMOS-only. Fig. 7 shows the phase noise performance. The measured phase noise is from -88.6 to -92.3 dBc/Hz at 1 MHz offset frequency. The phase noise of the proposed VCO is 2 dB lower than AMOS-only varactor VCOs at 1 MHz offset.

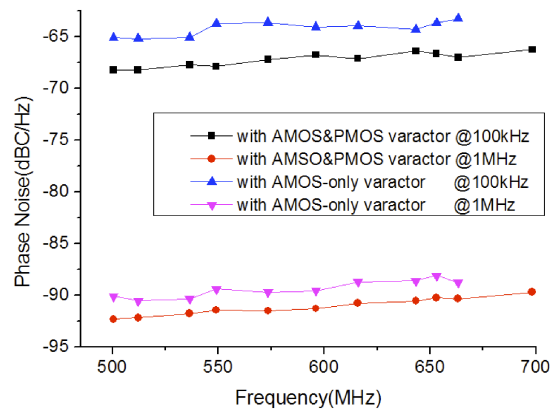


Fig. 7. Measured phase-noise performance at 100 kHz and 1 MHz offset

4 Conclusion

A linearized tuning varactor for VCOs has been proposed in this paper. By combining the AMOS and PMOS in parallel to form the varactor, its C - V characteristic is linearized. To obtain a monotonic C - V function for the PMOS varactors, the tuning voltage is connected with the PMOS varactor's n -well bulk, and a negative substrate bias voltage is applied to avoid entering the inversion region. Two ring VCOs using the proposed combined varactor and a conventional AMOS have been implemented with a standard 65 nm CMOS process, respectively. Measurement results have confirmed the K_{VCO} equalization.

Acknowledgments

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