A 7-Decades Tuning Range CMOS OTA-C Sinusoidal VCO

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Abstract

A new OTA-C based sinusoidal VCO has been designed and fabricated whose oscillation frequency can be tuned from 74*mHz* to 1*MHz*. The VCO uses a new OTA whose transconductance is adjusted by using a set of special current mirrors. These current mirrors operate in weak inversion and their gain can be controlled continuously through a gate voltage over many decades. To our knowledge such a wide tuning range has never been reported before for CMOS sinusoidal oscillators. Experimental results are provided.

I. A New CMOS Current Mirror

Fig. 1(a) shows a new active input current mirror, where a differential input voltage amplifier drives the transistor sources instead of the gates [1]. If transistors M_1 and M_2 are identical and operate in weak inversion,

$$I_o = I_{in} e^{\frac{V_{G2} - V_{G1}}{nU_T}} \tag{1}$$

where the gain of the current mirror is controlled exponentially by $V_{G2} - V_{G1}$, and this anticipates a very wide tuning range for this mirror. Figs. 2(a)-(b) show transconductance amplifiers [2] which can be used for the differential input voltage amplifier of Fig. 1(a). They are compensated for stability through their load capacitance C_{pa}, so that if they are connected in unity feedback configuration (see Fig. 2(c), and Fig. 2(d) for its small signal equivalent circuit), the stability condition is

$$C_{pa} > \frac{g_{ma}}{\omega_a} \tag{2}$$

where $g_m(s) = g_{ma}(1 - s/\omega_a)$ defines the frequency response for the transconductance of the circuit in Figs. 2(a)-(b), g_{ma} being the DC transconductance, and ω_a modeling the delay introduced by the internal nodes [3]. Fig. 1(b) represents the small signal equivalent circuit for the input stage of the mirror in Fig. 1(a), where g_{oa} is the output conductance of the voltage amplifier, g_{m1} is the transconductance for M_1 and g_{o1} its output conductance. Assuming eq. (2) is satisfied, the following condition guarantees stability

$$C_p > \frac{g_{ma} g_{m1}}{\omega_a (g_{oa} + g_{m1})} \tag{3}$$

Since the right hand side of eq. (3) is an increasing function of g_{m1}, once it is satisfied for the maximum g_{m1} (maximum I_{in}) the circuit remains stable for any smaller input current. If eq. (3) cannot be satisfied (or a poor phase margin results), a compensation capacitor can be added between nodes v_1 and v_2 in Fig. 1. Note that in this analysis we have neglected the current through M_2. It can be verified that by taking into account this current, the stability conditions are relaxed. Therefore, eq. (3) provides the worst case stability condition.

II. Constant Linear Input Range OTA

Fig. 3(a) shows a conventional OTA (as in Fig. 2(d)) in which the current mirrors have been changed by those of the type in Fig. 1(a). The two top ones are adjustable through $V_{G2} - V_{G1}$ and the bottom one is of constant unity gain. In a conventional OTA the transconductance is controlled through I_{ss} which deteriorates its linear input range as I_{ss} decreases. This is illustrated in Fig. 4(a) where g_m is tuned between $30\mu A/V$ and $60pA/V$ through I_{ss} (with $V_{G1} = V_{G2}$). The figure shows the OTA output current normalized with respect I_{ss}. On the other hand, if I_{ss} is set to its maximum value and V_{G2} is used to tune the OTA, the normalized curves in Fig. 4(b) result. As can be seen, the linear input range of the OTA is not degraded when g_m is changed from $30\mu A/V$ to $40pA/V$. This is very convenient for low distortion sinusoidal OTA-C based VCOs, since they must operate in the linear range of their OTAs.

III. Sinusoidal OTA-C VCO

Fig. 3(b) shows the circuit diagram of a quadrature OTA-C sinusoidal VCO , where OTA g_{mp} is connected to emulate a positive resistor to compensate for the phase shift of the g_{mo} OTAs [3]. Its oscillation frequency is $f_{VCO} = g_{mo}/(2\pi C)$. A VLSI prototype has been fabricated in a $1\mu m$ CMOS process. Voltage V_{G1} of the g_{mo} OTAs was set to $3.5V$, while V_{G2} was swept from $3.5V$ to $4.12V$. The resulting VCO frequency vs. V_{G2} tuning curve is shown in Fig. 5, where the VCO sinusoids frequency changed from $1.015MHz$ to $73.96mHz$. Fig. 6 shows the measured waveforms for the maximum and minimum frequencies. To our knowledge, a CMOS sinusoidal VCO with such a wide tuning range has never been reported before.

IV. References

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[3] Bernabé Linares-Barranco, Angel Rodríguez-Vázquez, José L. Huertas, and Edgar Sánchez-Sinencio, "On the Generation Design and Tuning of OTA-C High Frequency Sinusoidal Oscillators," *IEE Proceedings-Part G, Circuits Devices and Systems*, vol. 139, No. 5, pp. 557-568, October 1992.

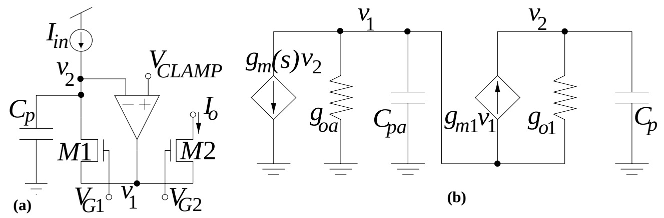

Fig. 1: Schematic diagram of the new active-input tunable current mirror

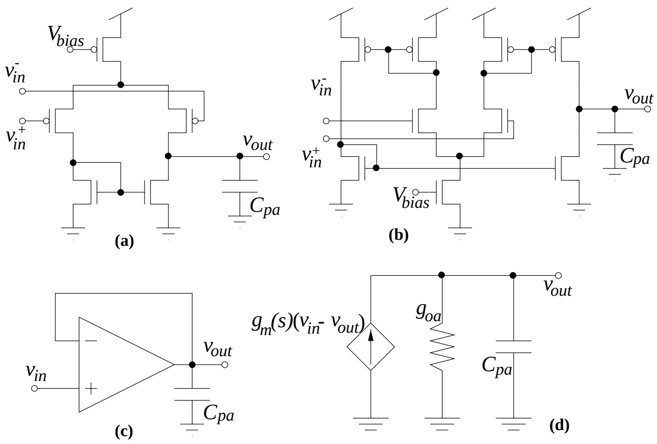

Fig. 2: Simple OTA structures suitable for the differential input voltage amplifier. (a) Five transistor OTA for n-type current mirrors, (b) nine transistor full range OTA, (c) unity gain feedback configuration, (d) small signal equivalent circuit for unity gain feedback configuration.

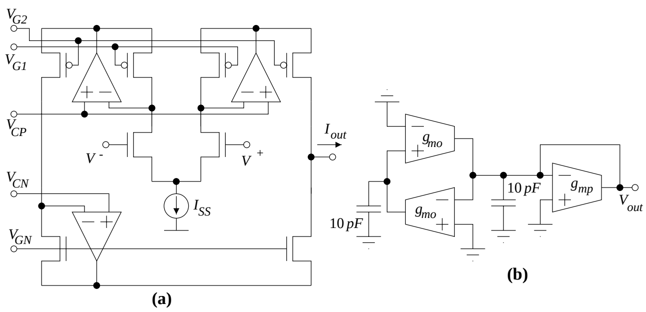

Fig. 3: (a) Constant Linear Input Range OTA, (b) Sinusoidal OTA-C VCO

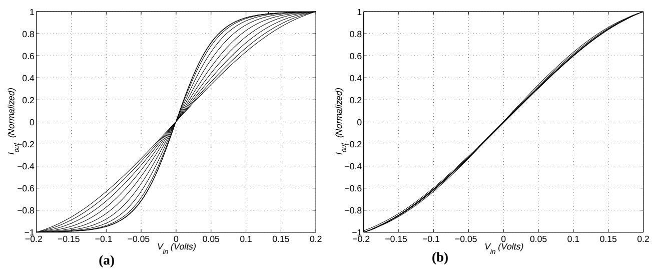

Fig. 4: Experimentally measured dependence of OTA linear input range on transconductance tuning. Normalized OTA output current as a function of differential input voltage, for (a) tuning through I_{SS}, (b) or through V_{G2}.

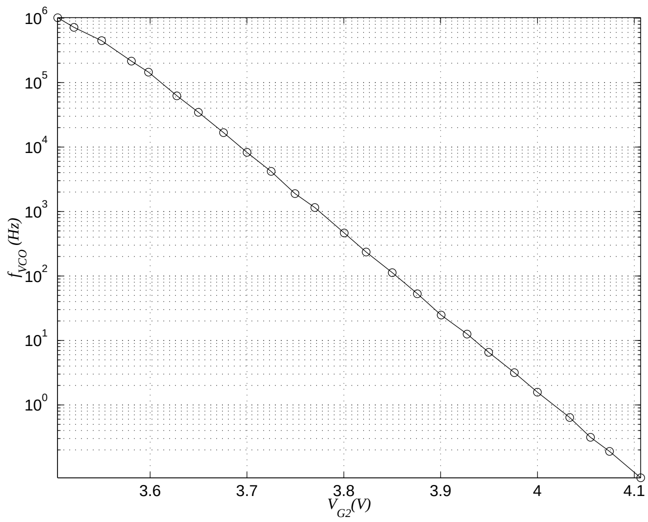

Fig. 5: Experimentally Measured Relationship between Sinusoidal VCO Frequency and Control Voltage V_{G2}.

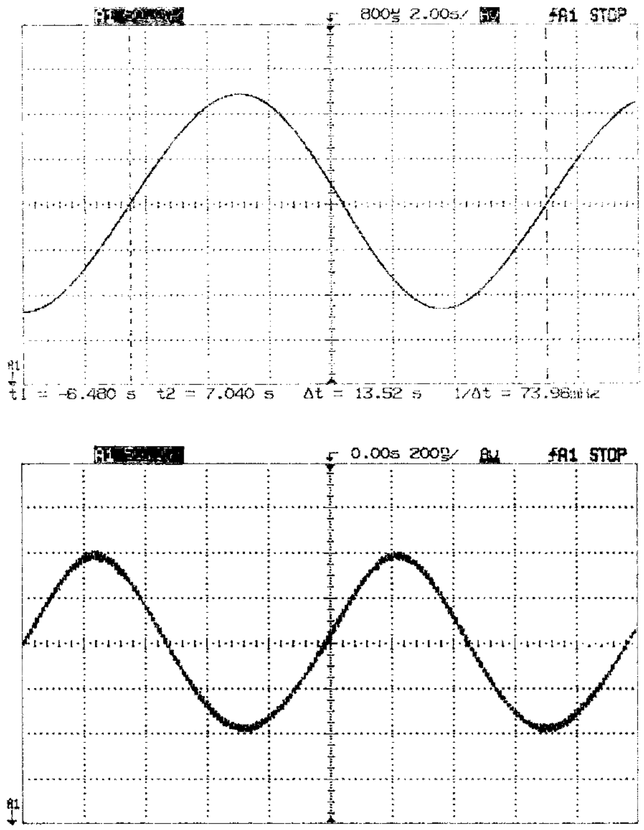

Fig. 6: Measured VCO outputs for minimum (73.94mHz) and maximum (1.015MHz) frequencies. Vertical scale is 50*mV/div* and horizontal scales are 2s/div and 200ns/div respectively.