

Report on the design of scalable VCO in CMOS technology

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1 Description of the VCO architecture

The VCO is a ring oscillator composed from a looped chain of individual inverting delay cells. The delay cells are CMOS inverters where the currents of the transistors are controlled by two current limiters MPC and MNC. The control of the MNC current source is achieved directly by the input control voltage V_{ctrl} , the transistors MP1 and MN1 generates a control voltage for the P transistor (MP1 and MPC, MN1 and MNC form current mirrors with ratio 1 :1).

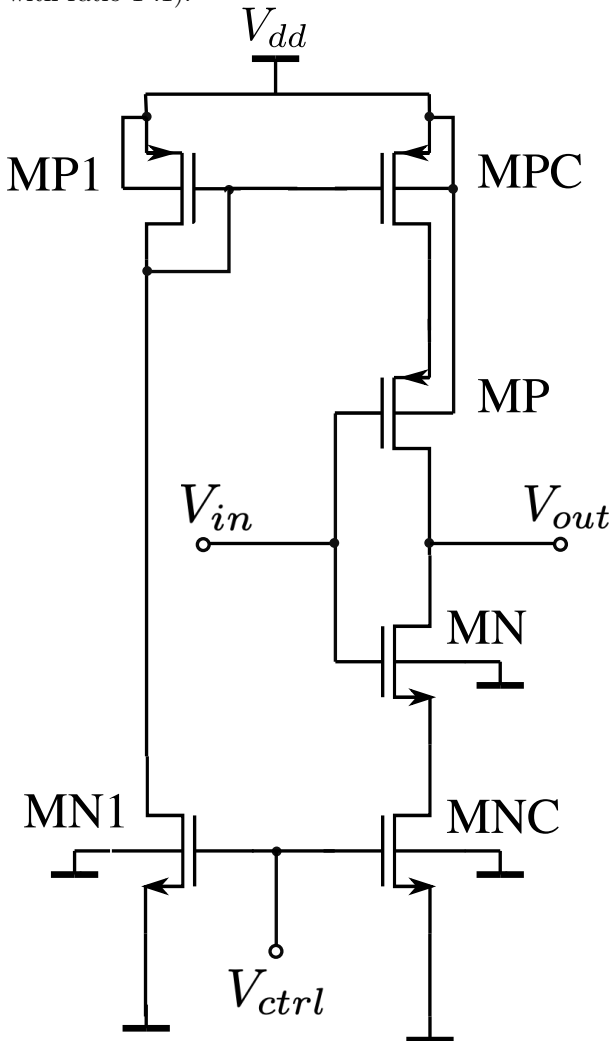


FIGURE 1 – Schematic of a delay cell.
The delay of a CMOS inverter can be estima-

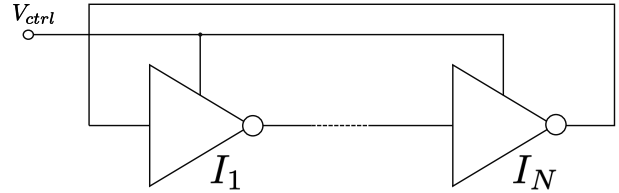


FIGURE 2 – Architecture of the VCO.

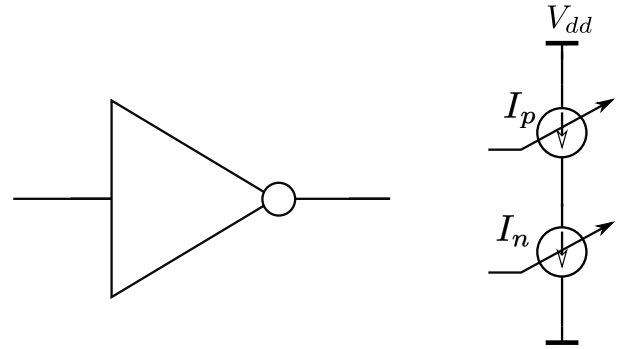


FIGURE 3 – Inverter switching model.

ted, considering that that the output (load) capacitor charges from 0 or discharges from V_{dd} to $V_{th}=V_{dd}/2$ through the transistors PMOS or NMOS which can be seen as controlled current sources (fig. 3), see J. Rabaey, Digital Integrated Circuits, sec. 3.3.

These transistors may be considered as being in saturation all the time till the output capacitor voltage reaches $V_{dd}/2$. During this time the current source (the transistor MP or MN) generate a current I_{ch} . Hence, as the input changes from 0 to 1 (for example), the output capacitor C_L needs some time to discharge from V_{dd} to $V_{dd}/2$ through the

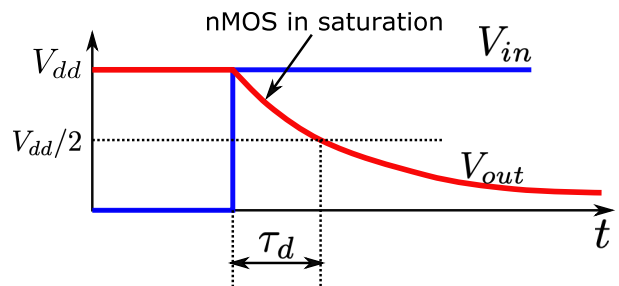


FIGURE 4 – Inverter switching diagram (from 1 to 0).

nMOS transistor (fig. 4). This delay is given by

$$\tau_d = \frac{Q}{I_{ch}} = \frac{C_L V_{dd}/2}{I_{ch}} \quad (1)$$

Here Q is the total charge variation on the capacitor while the output voltage goes from 0 or 1 to $V_{dd}/2$.

If cell is well balanced, the charge and discharge currents are equal and the above defined quantity τ_d may be considered as the delay of the cell.

Hence, the frequency of a ring oscillator composed out of N such cells (N is odd) is given by

$$f = \frac{1}{2N\tau_d} = \frac{I_{ch}}{NC_L V_{dd}} \quad (2)$$

The load capacitor C_L is composed of the output capacitors of the cell and of the input capacitors of the subsequent cell in the chain.

The cell capacitors can be obtained from the operating point analysis performed with the following biasing : $V_{gs} = V_{ds} = \pm V_{dd}/2$ according to the type of the transistor.

The simulator provide the value of the total capacitors connected to the drain and gate nodes, cgg and cdd . The total load capacitance is the sum of the drain and gate capacitors of PMOS and NMOS transistors, $C_l = cgg_n + cdd_n + cgg_p + cdd_p$.

The current I_{ch} is calculated for one of the transistors with $V_{gs} = V_{ds} = \pm V_{dd}$.

This calculation allows one to obtain the maximum oscillation frequency, when the control voltage is maximum (V_{dd}) and when the current limiting transistors are much larger than the cell transistors. Typically, when the ratio between the widths of the core transistors MN and MP W_n , W_p and the current limiting transistors MNC and Mpc W_{nc} , W_{pc} defined as $K = W_c/W$ is equal to 3, the presence of the current limiting transistors has negligible impact on the maximum oscillating frequency.

As the ratio K is reduced (e.g., to 1), even when V_{ctrl} has a maximum value (V_{dd}), the maximum oscillating frequency is less than one predicted by the formulae (1), and needs to be determined by simulation.

The ratio K should not be too big, since if MPC and MPN are large, the input capacitance of the *ctrl* input is larger and the control will need more power. We advise the optimal ratio K . Its value should only be increased if a higher oscillation frequency is required, and the maximum value should be K .

2 Sizing algorithm

Here we describe the sizing algorithm. The example of its application will be given for the technology AMS C35 (350 nm), with the target maximum frequency of the VCO 300 MHz.

1. The first step consists in sizing a balanced CMOS cell with $V_{th} = V_{dd}/2$. For that :
 - (a) We fix W_n to the minimum value of the technology, W_{nmin}
 - (b) We calculate the current I_n of the nMOS transistor for $V_{gs} = V_{ds} = V_{dd}/2$
 - (c) We calculate the width of the pMOS transistor W_p for $V_{gs} = V_{ds} = -V_{dd}/2$ so to obtain the current I_n determined in the previous step.

Result of the test case : the ratio is 3.2.

Only the ratio between the widths W_p and W_n is relevant. The frequency of the ring oscillator does not change if all widths are multiplied by a factor. This is true in "old" technologies, where transistor parasitic capacitors dominate comparing to the wire capacitors. It is less true for deep submicronic technologies, where the layout design may have a strong impact on the oscillation frequency especially when the transistor sizes are close to the minimum.

2. Before performing the sizing, we provide the characterisation of a 5 stage oscillator for a given technology with the following parameters :

- (a) $L=L_{min}$, $K=3$, $V_{ctrl}=0...V_{dd}$

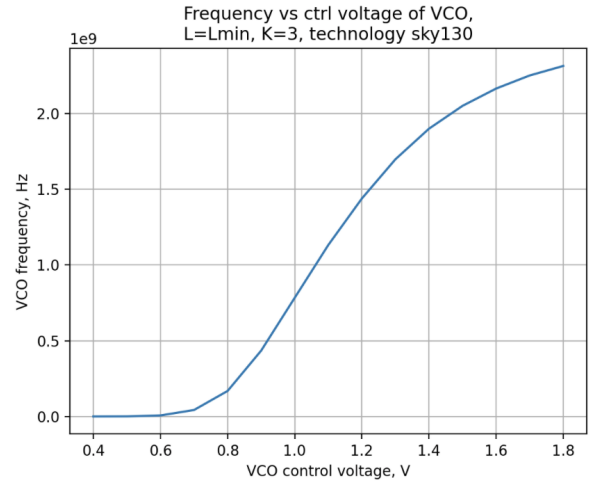


FIGURE 5 – Oscillating frequency vs V_{ctrl} frequency : minimum L , $K=3$, application to the selected test case.

- (b) For $V_{ctrl} = V_{dd}$ the corresponding oscillation frequency is the maximum that can be achieved.

$K=3$, $V_{ctrl}=V_{dd}$, $L=L_{min}...1\mu m$

This gives as the idea about how the maximum oscillation frequency changes with L .

3. After having a look on the two characteristics mentioned above, the user proposes the maximum oscillation frequency, f_{max} .
4. We measure the frequency f_{max1} corresponding to $V_{ctrl} = 0.8V_{dd}$, $L = L_{min}$ and $K = 1$.

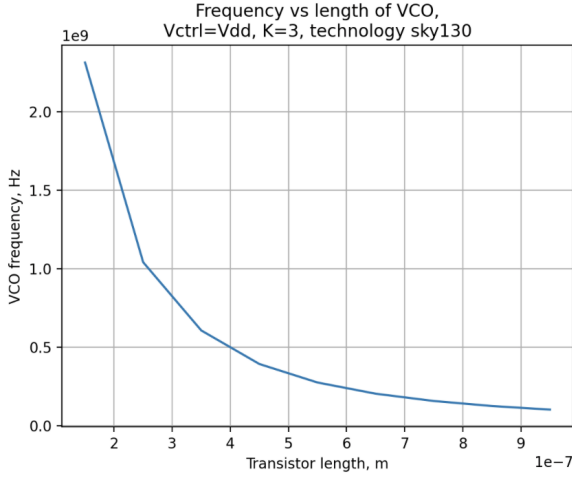


FIGURE 6 – Oscillating frequency vs L : $V_{ctrl} = V_{dd}$, $K=3$, application to the selected test case.

5. If $f_{max} < f_{max1}$: the sizing is feasible, go to the step 5.
6. If $f_{max} > f_{max1}$: we try to increase K setting $K = 3$. For $V_{ctrl} = 0.8V_{dd}$, $L = L_{min}$ and $K = 3$ we obtain a new frequency, f_{max2} .
7. If $f_{max} > f_{max2}$: the sizing is impossible and the user should reduce the requested frequency. The procedure stops.
8. Now we look for L (by increasing L) which gives the target f_{max} for $V_{ctrl} = 0.8V_{dd}$ and $K = 1$. Since the function "Frequency versus L " is strictly monotonic (decreasing), the finding algorithm is straightforward (e.g., the dichotomy), see the code for a practical implementation.
9. We display the output of a working oscillator for the calculated L and for the input voltages $V_{ctrl} = 0.8V_{dd}$ and $V_{ctrl} = 0.3V_{dd}$.
10. We display the voltage-frequency characteristics of the obtained VCO.

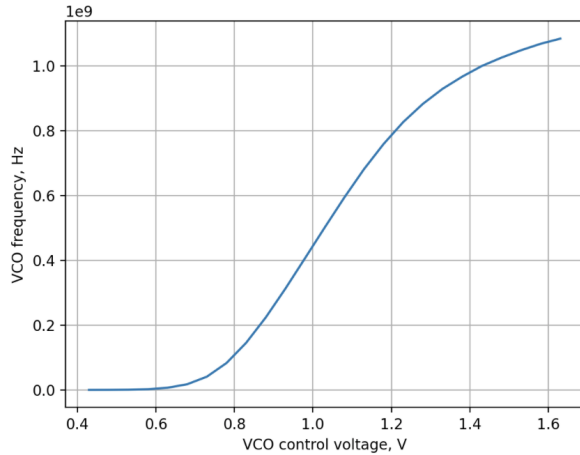


FIGURE 7 – Final voltage-frequency characteristic of the VCO for the test case.

3 Determination of the oscillating frequency

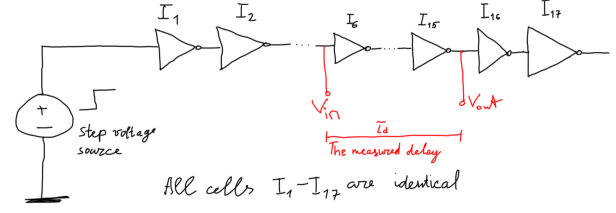


FIGURE 8 – Schematic allowing a measurement by simulation of a cell delay in the conditions identical to those of a ring oscillator.

Direct simulation of an oscillator for determination of the oscillation frequency is not convenient, since the simulation of an oscillator is generally an hazardous job (start-up problems, precision, adjustment of the simulation time to the frequency...). For this reason, the oscillation frequency is calculated from the delay of the cell, which is obtained by simulation of a chain of cells. This is much more robust and fast, because the circuit is open loop and the timing is easier to master. In order to get a realistic estimation of the delay, we simulate a chain of 17 identical cell, and we measure the delay between the input of the cell 6 and the output of the cell 15, see fig. 8. This yields 10 times the delay we want to determine. The fact of using 10 cells improve the precision of the measurement.

This is implemented in the netlist CMOS_delay_cell.scs.

The script calculating the delay of a cell with given parameters (transistor sizes, supply voltage, control voltage, etc.) is given in file CMOS_delay_cell.py.