EE230-02 RFIC II
Fall 2018

Lecture 14: Oscillators 3

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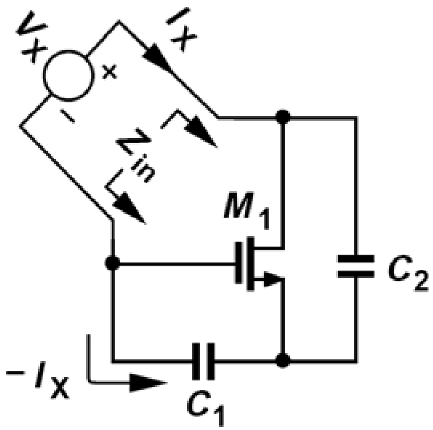
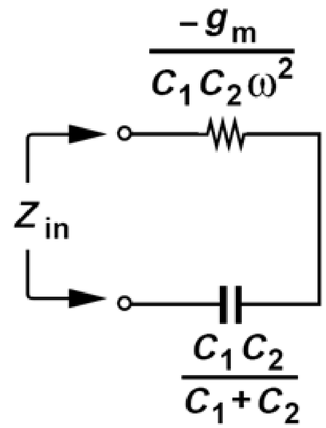
ENG-259

Midterm Exam

- **Oct. 16, Tuesday 4:30 PM**
- **One-page Aid sheet on Front side only allowed**
- **Bring a copy of your Aid sheet**
  - **Write your name and submit it for extra 5 points**
- **Bring your Calculator**

How Can a Circuit Present a Negative Input Resistance?





$$-\frac{I_X}{C_1 s} + V_X = \left(I_X + I_X \frac{g_m}{C_1 s}\right)\frac{1}{C_2 s}$$

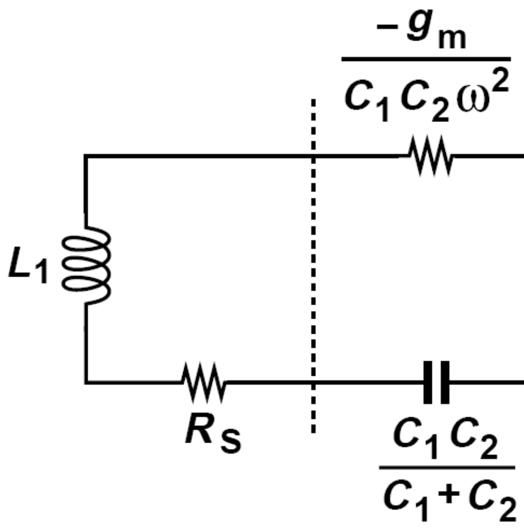
$$\frac{V_X}{I_X}(s) = \frac{1}{C_1 s} + \frac{1}{C_2 s} + \frac{g_m}{C_1 C_2 s^2}$$

$$\frac{V_X}{I_X}(j\omega) = \frac{1}{jC_1\omega} + \frac{1}{jC_2\omega} - \frac{g_m}{C_1 C_2 \omega^2}$$

- **The negative resistance varies with frequency.**

Connection of Lossy Inductor to Negative-Resistance Circuit

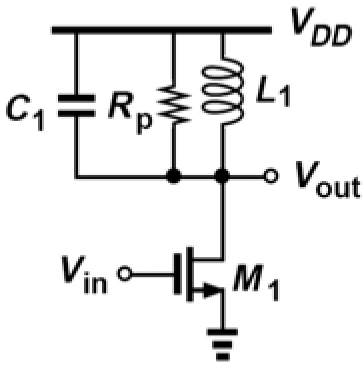
- **Connect an inductor to the negative-resistance port to create a resonant tank**

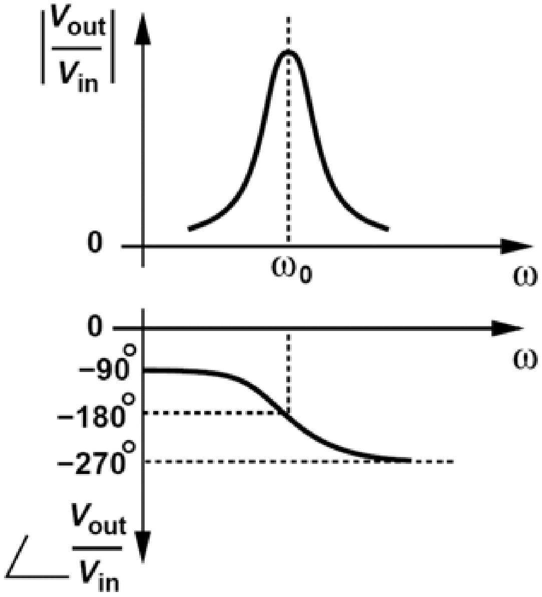


$$R_S = \frac{g_m}{C_1 C_2 \omega^2} \qquad \omega_{osc} = \frac{1}{\sqrt{L_1 \frac{C_1 C_2}{C_1 + C_2}}}$$

Tuned Oscillator

Negative-feedback oscillatory system using "LC-tuned" amplifier stages





Can this circuit oscillate if its input and output are shorted?
NO!

At very low frequencies, L_1 dominates the load and

$$\frac{V_{out}}{V_{in}} \approx -g_m L_1 s$$

$|V_{out}/V_{in}|$ is very small and $\angle(V_{out}/V_{in})$ remains around -90°

At the resonance frequency

$$\frac{V_{out}}{V_{in}} = -g_m R_p$$

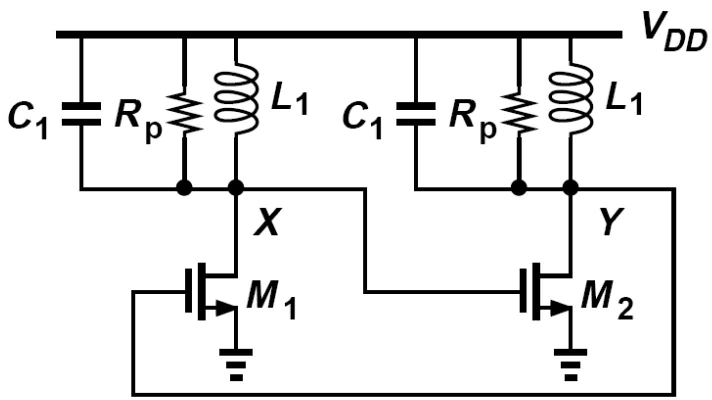
The phase shift from the input to the output is thus equal to -180°

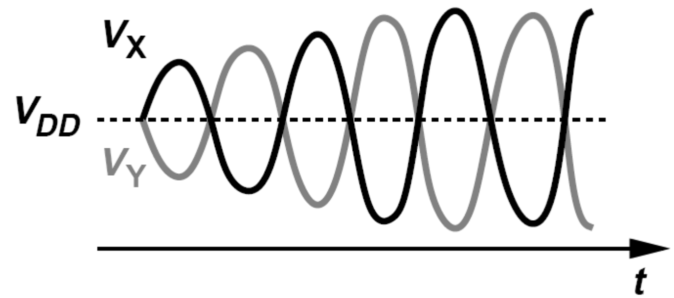
At very high frequencies

$$\frac{V_{out}}{V_{in}} \approx -g_m \frac{1}{C_1 s}$$

$|V_{out}/V_{in}|$ diminishes $\angle(V_{out}/V_{in})$ approaches -270°

Cascade of Two Tuned Amplifiers in Feedback Loop



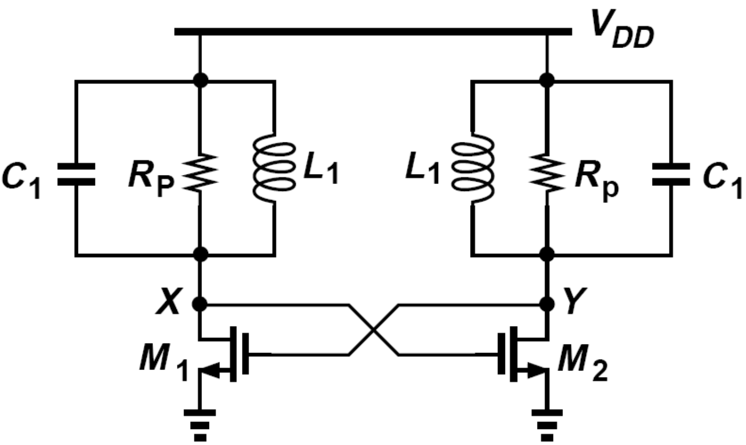


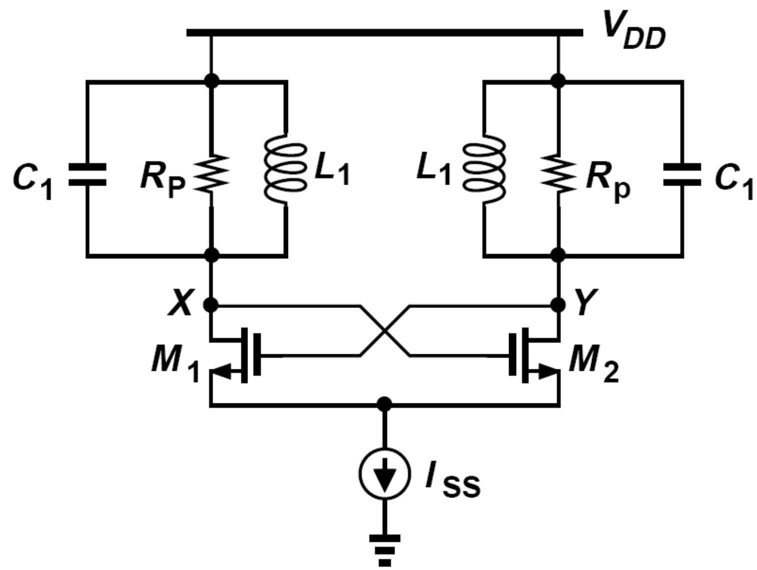
$$(g_m R_p)^2 \geq 1$$

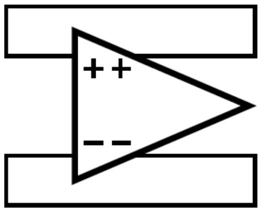
A unique attribute of inductive loads

- **Peak voltages above the supply**
- **The growth of V_X and V_Y ceases when M_1 and M_2 enter the triode region**

Cross-Coupled Oscillator





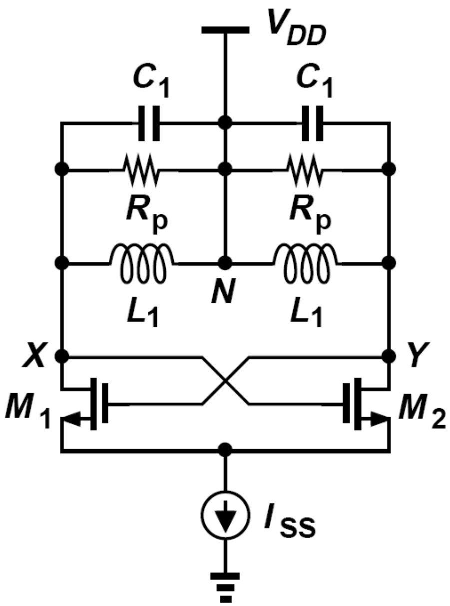


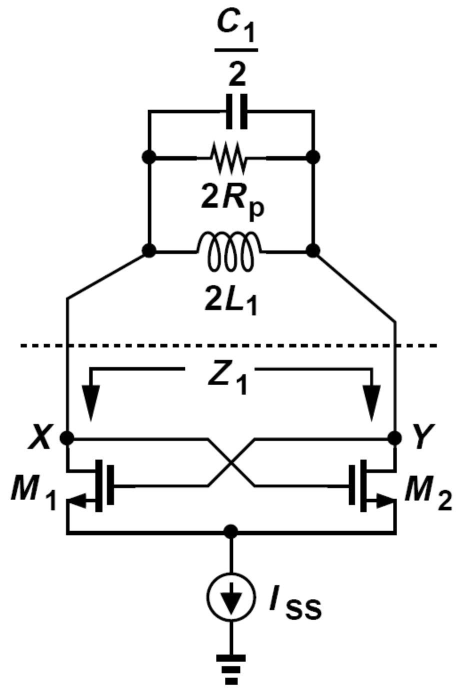
$$\omega_{osc} = \frac{1}{\sqrt{L_1(C_{GS2} + C_{DB1} + 4C_{GD} + C_1)}}$$

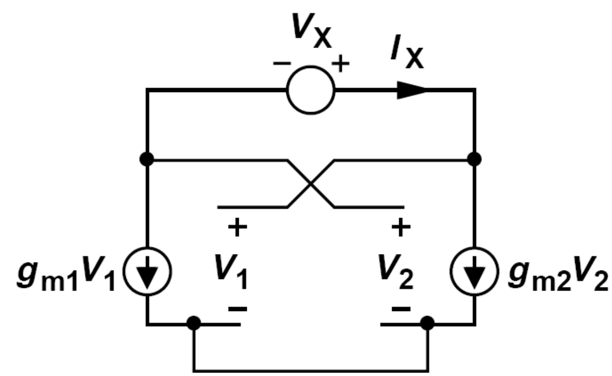
Left circuit suffers from poorly-defined bias currents.
Middle circuit is more robust and can be viewed as an inductively-loaded differential pair with positive feedback.

$$V_{XY} \approx \frac{4}{\pi} I_{SS} R_p$$

One-Port View of Cross-Coupled Oscillator







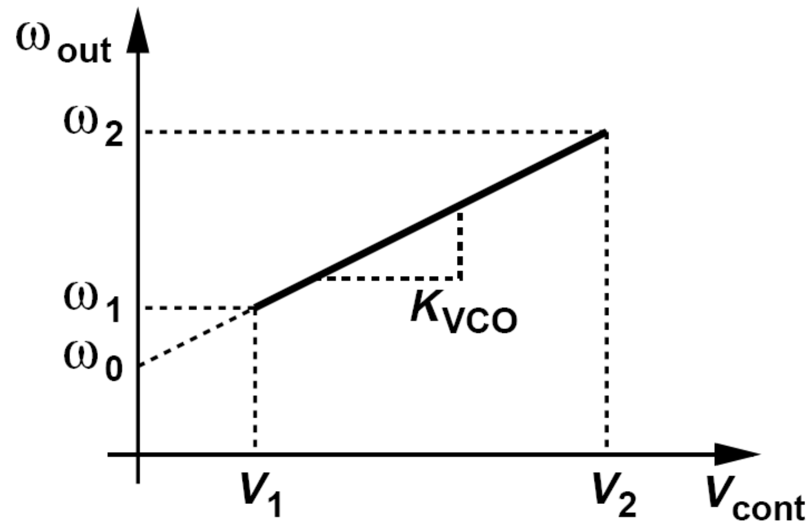
$$I_X = -g_{m1}V_1 = g_{m2}V_2 \Rightarrow \frac{V_X}{I_X} = -\left(\frac{1}{g_{m1}} + \frac{1}{g_{m2}}\right)$$

For $g_{m1} = g_{m2} = g_m$ $\quad \frac{V_X}{I_X} = -\frac{2}{g_m}$

For oscillation to occur,
the negative resistance must cancel the loss of the tank:

$$\frac{2}{g_m} \leq 2R_p \Rightarrow g_m R_p \geq 1$$

Voltage-Controlled Oscillators: Characteristic

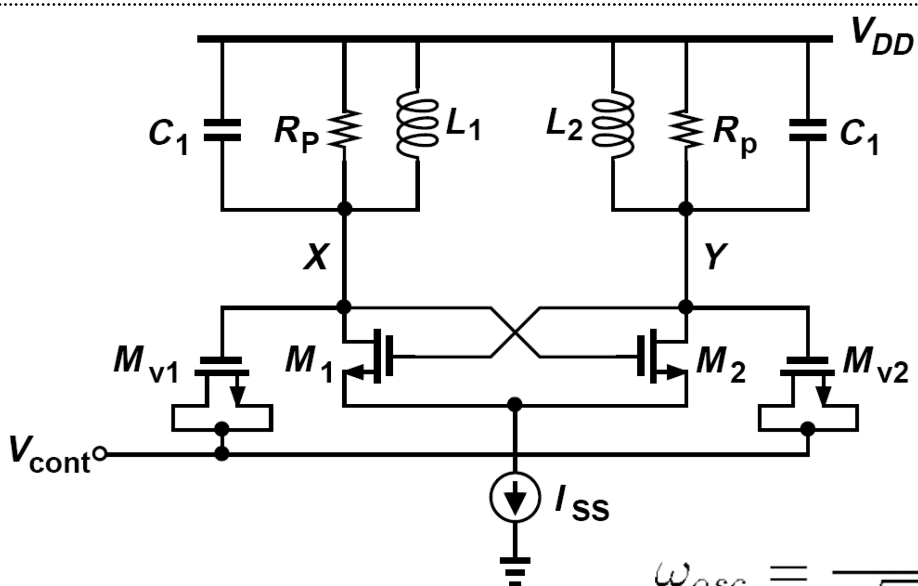


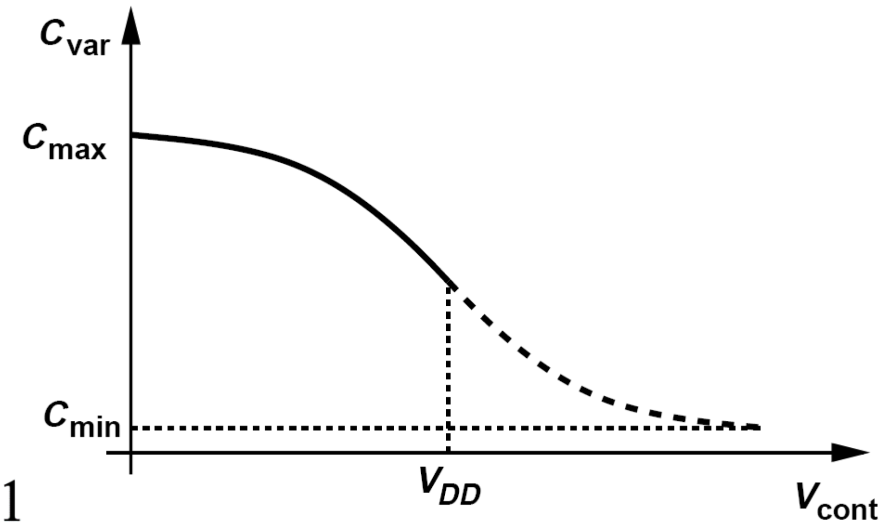
$$\omega_{out} = K_{VCO} V_{cont} + \omega_0$$

- The frequency varies from ω_1 to ω_2 (the required tuning range) as the control voltage, V_{cont}, goes from V_1 to V_2
- The slope, K_{VCO}, is called the "gain" or "sensitivity" of the VCO and expressed in rad/s/V.

VCO Using MOS Varactors

- Since it is difficult to vary the inductance electronically,
  we vary the capacitance by means of a varactor.
- MOS varactors are more commonly used than *pn* junctions, especially in low-voltage design.





$$\omega_{osc} = \frac{1}{\sqrt{L_1(C_1 + C_{var})}}$$

- First, the varactors are stressed for part of the period if V_{cont} is near ground and V_X (or V_Y) rises significantly above V_{DD}.
- Second, only about half of C_{max} - C_{min} is utilized in the tuning.

Varactors

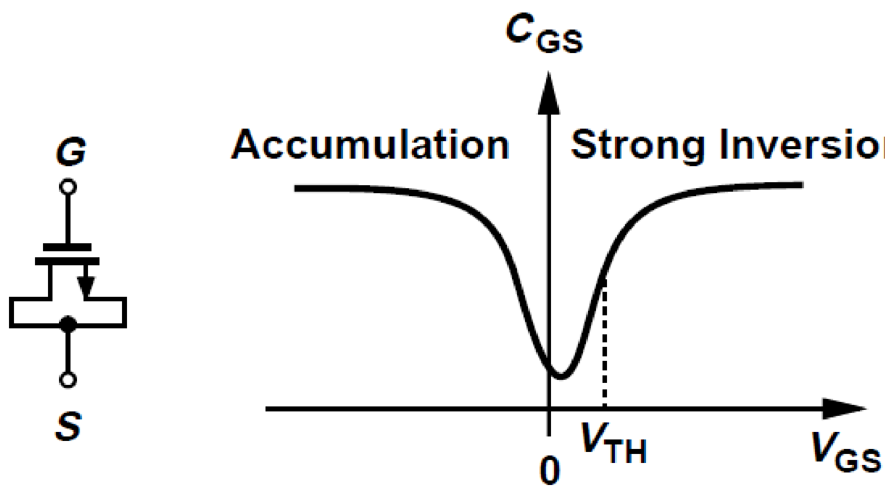
Varactor is a voltage-dependent capacitor.

Two important attributes of varactor design become critical in oscillator design

- **The capacitance range i.e. ratio of maximum to minimum capacitance that varactor can provide.**
- **The quality factor of the varactor.**

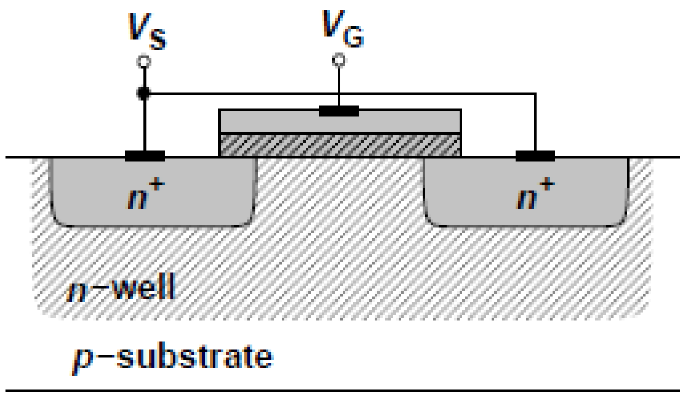
MOS Varactors

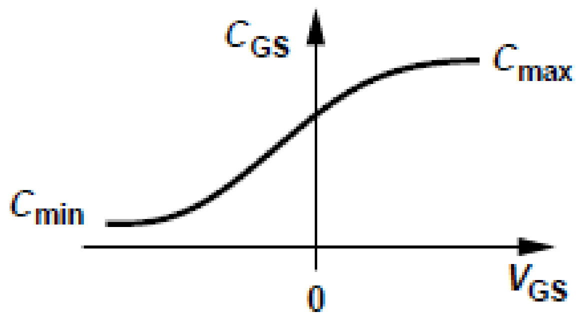
Regular MOS device:



Variation of gate capacitance with Vgs

Accumulation Mode MOS Varactor

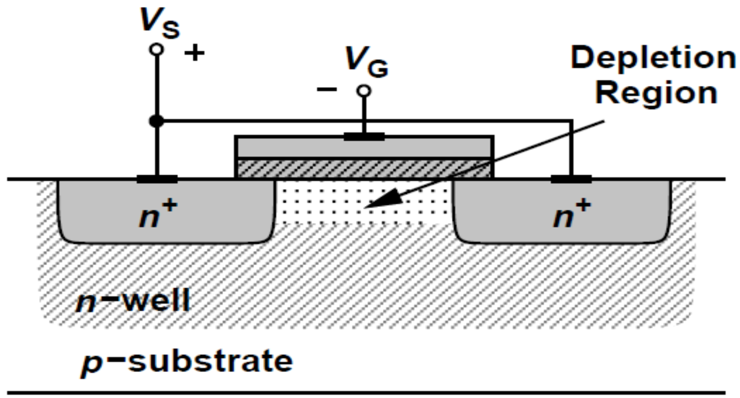




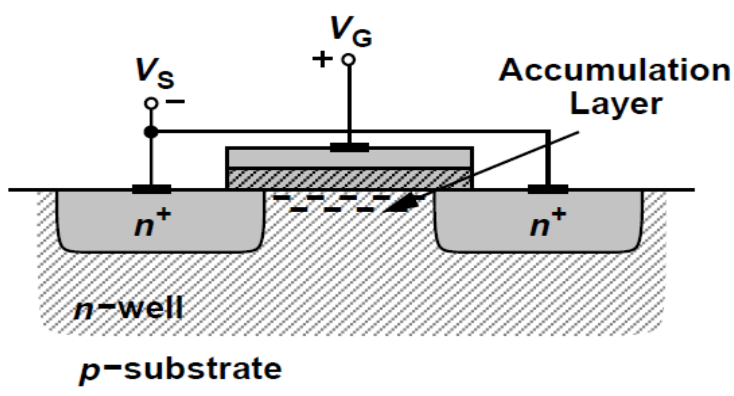
C/V characteristics of varactor

- Accumulation-mode MOS varactor is obtained by placing an NMOS inside an nwell .
- The variation of capacitance with Vgs is monotonic.
- The C/V characteristics scale well with scaling in technology.
- Unlike PN junction varactor this structure can operate with positive and negative bias so as to provide maximum tuning range.

Accumulation Mode MOS Varactor Operation



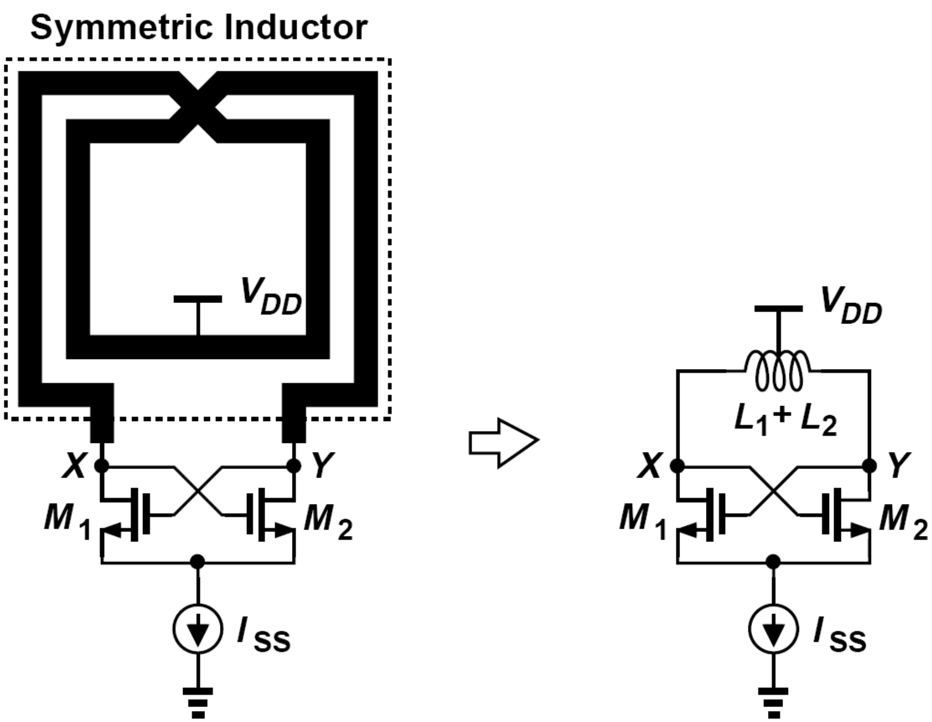
- Vg < Vs
- Depletion region is formed under gate oxide.
- Equivalent capacitance is the series combination of gate capacitance and depletion capacitance.



- Vg > Vs
- Formation of channel under gate oxide.

Oscillator Using Symmetric Inductor

- Symmetric spiral inductors excited by differential waveforms exhibit a higher *Q* than their single-ended counterparts.



$L_1 = L_2 = 1$ nH
Q = 10 at 10 GHz

What is the minimum required transconductance of M_1 and M_2 to guarantee start-up?

$$g_{m1,2} \geq (630\ \Omega)^{-1}$$

Tuning Range Limitations

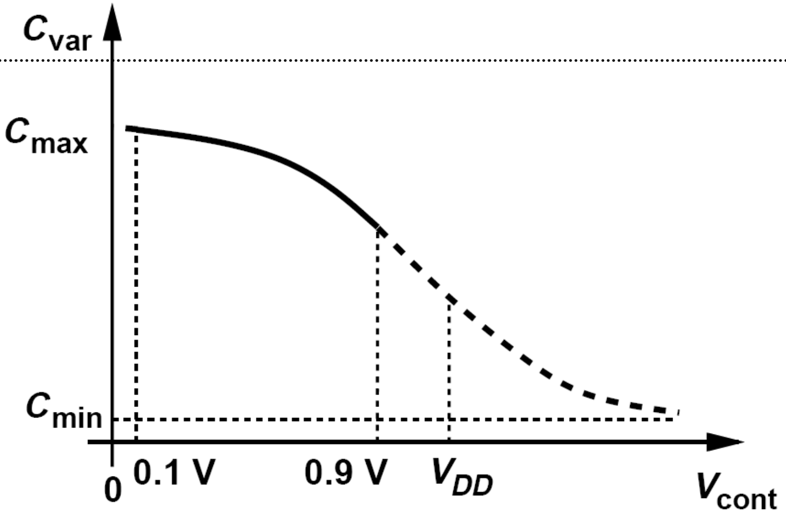
If $C_{var} << C_1$, then

$$\omega_{osc} \approx \frac{1}{\sqrt{L_1 C_1}}\left(1 - \frac{C_{var}}{2C_1}\right)$$

If the varactor capacitance varies from C_{var1} to C_{var2}, then the tuning range is given by

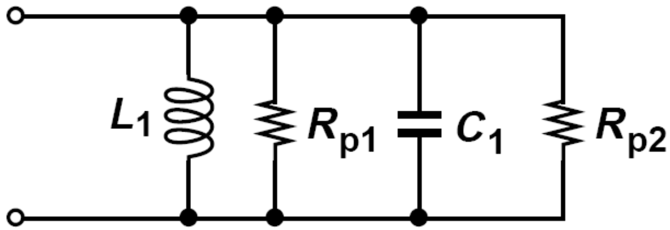
$$\Delta\omega_{osc} \approx \frac{1}{\sqrt{L_1 C_1}} \frac{C_{var2} - C_{var1}}{2C_1}$$

- **Another limitation on C_{var2} - C_{var1} arises from the available control voltage range of the oscillator, $V_{cont.}$**



Effect of Varactor Q: Tank Consisting of Lossy Inductor and Capacitor

A lossy inductor and a lossy capacitor form a parallel tank. Determine the overall *Q* in terms of the quality factor of each.



$$Q_L = \frac{R_{p1}}{L_1\omega}$$
$$Q_C = R_{p2}C_1\omega$$

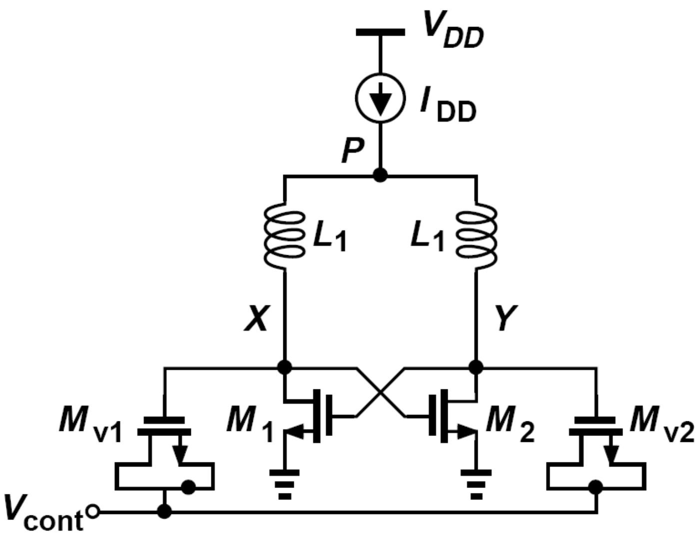
Merging R_{p1} and R_{p2} yields the overall *Q*:

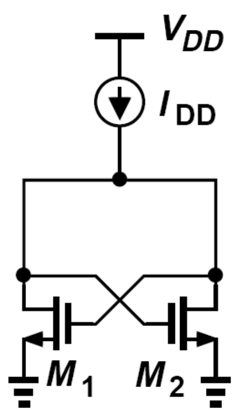
$$Q_{tot} = \frac{R_{p1}R_{p2}}{R_{p1}+R_{p2}} \cdot \frac{1}{L_1\omega}$$
$$= \frac{1}{\dfrac{L_1\omega}{R_{p1}} + \dfrac{L_1\omega}{R_{p2}}}$$
$$= \frac{1}{\dfrac{L_1\omega}{R_{p1}} + \dfrac{1}{R_{p2}C_1\omega}}.$$

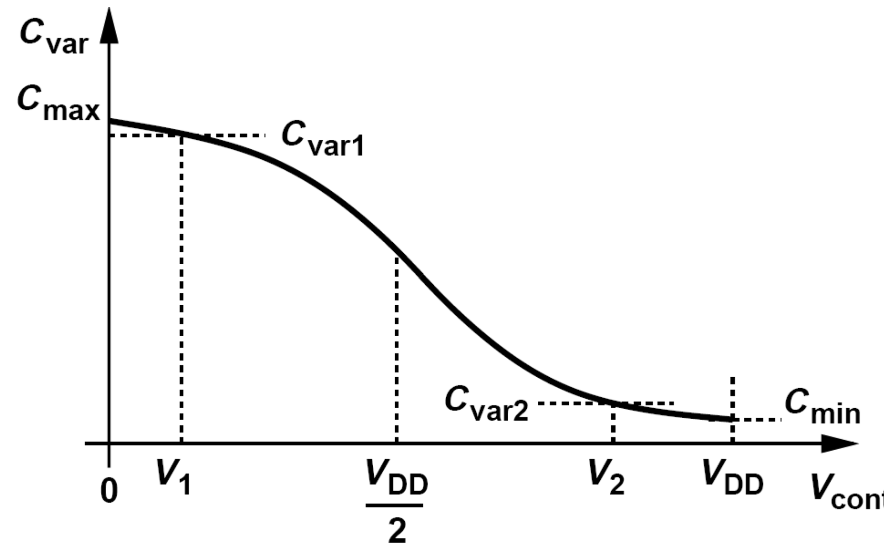
$$\Rightarrow \quad \frac{1}{Q_{tot}} = \frac{1}{Q_L} + \frac{1}{Q_C}$$

LC VCOs with Wide Tuning Range: VCOs with Continuous Tuning

- We seek oscillator topologies that allow both positive and negative (average) voltages across the varactors, utilizing almost the entire range from C_{min} to C_{max}.







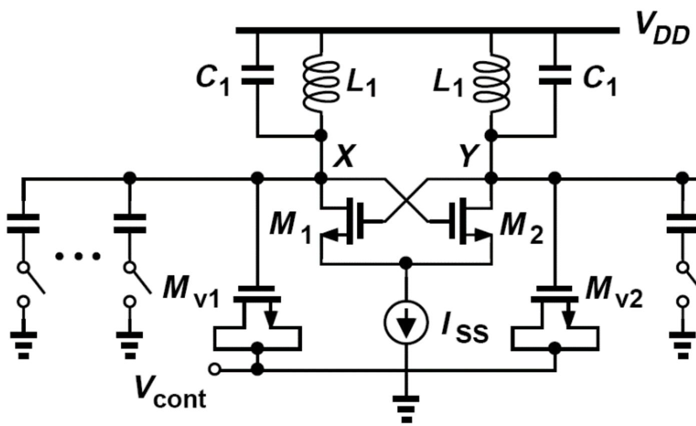
The CM level at X & Y:

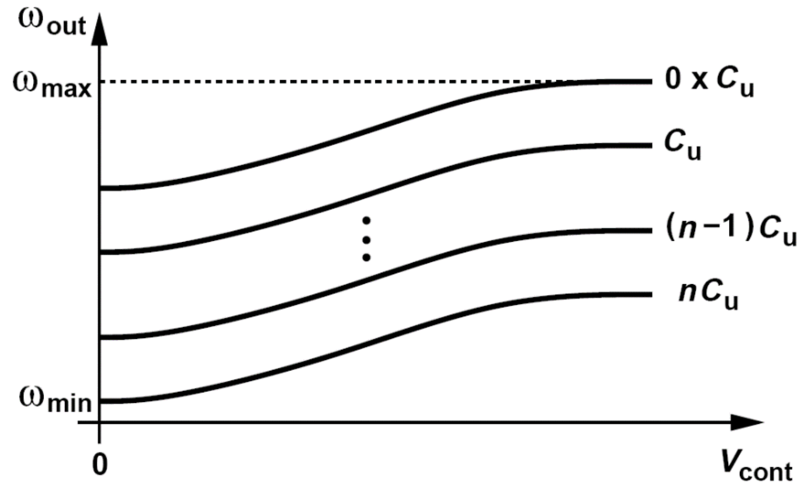
$$V_{GS1,2} = \sqrt{\frac{I_{DD}}{\mu_n C_{ox}(W/L)}} + V_{TH}$$

Select the transistor dimensions such that the CM level is approximately equal to $V_{DD}/2$.
As V_{cont} varies from 0 to V_{DD},
the gate-source voltage of the varactors, $V_{GS,var}$, goes from $+V_{DD}/2$ to $-V_{DD}/2$,

Discrete Tuning

- In applications where a substantially wider tuning range is necessary, "discrete tuning" may be added to the VCO so as to achieve a capacitance range well beyond C_{max}/C_{min} of varactors.





$$\omega_{min} = \frac{1}{\sqrt{L_1(C_1 + C_{max} + nC_u)}}$$

$$\omega_{max} = \frac{1}{\sqrt{L_1(C_1 + C_{min})}}$$