Lecture 8

of

EEE307

Electronics for Communications

Department of Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 8th November 2019

- ❑ Positive Feedback for Oscillation
- ❑ Ring Oscillator & LC Oscillator
- ❑ **Voltage-Controlled Oscillator (VCO)**
  - ➢ use of **varactors**
- ❑ Phase Noise

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Oscillators for Signal Generation

(applications)

- **Oscillators** are used extensively for **signal generation** in various electronic systems. Their applications range from clock generation in microprocessors to synthesis of carrier signals in wireless communication systems.
  - The oscillator topologies and performance consideration can vary considerably depending on the applications.
  - Common types of oscillators include **ring oscillators** and **LC oscillators** in generating ***periodic*** electrical signals.
  - Usually, oscillators are embedded in phase-locked systems.

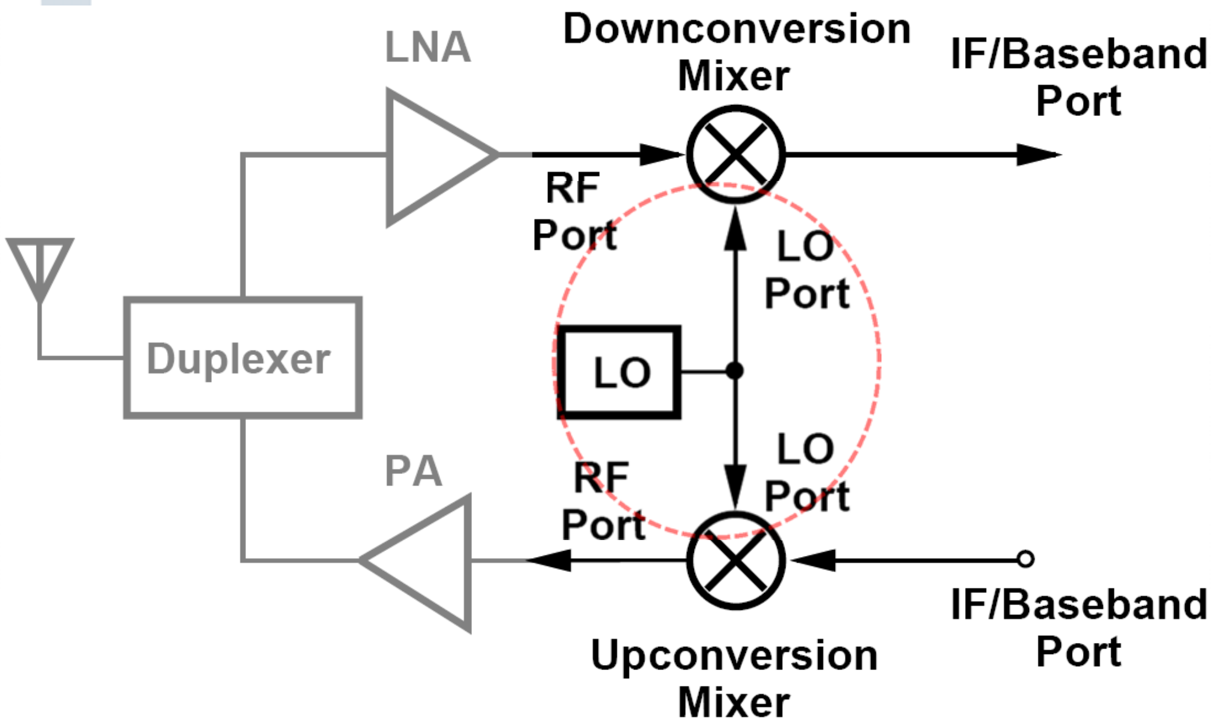
Xi'an Jiaotong-Liverpool University
西交利物浦大学

Oscillators for Signal Generation

(radio communication system)

- In a wireless communication system, a ***periodic* local oscillator** (LO) signal is needed to drive one input of the mixers in the transmit and receive paths.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.



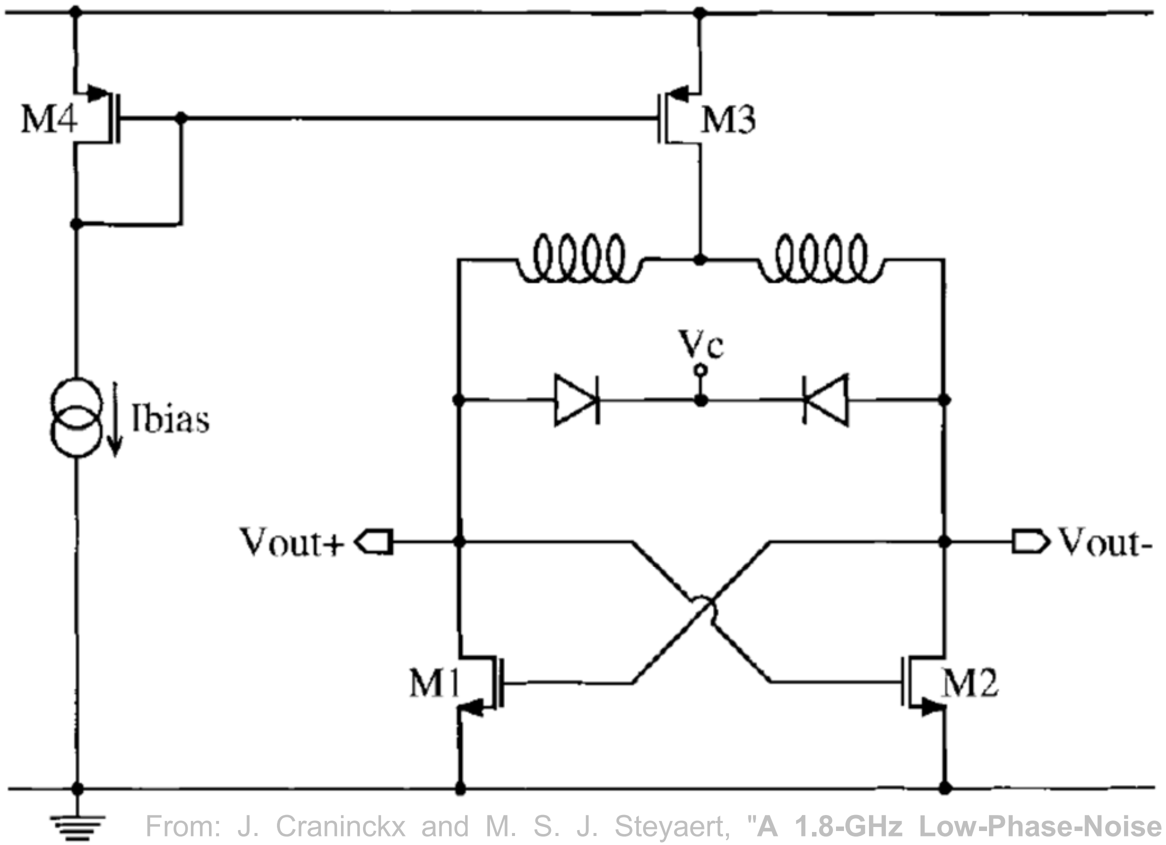
- **Oscillators**, in particular, ***tuneable* oscillators** are indispensable in radio communication and optical communication systems.

Xi'an Jiaotong-Liverpool University 西交利物浦大学

CMOS VCO Example

(using spiral inductors & varactors)

- A 1.8-GHz low-phase-noise CMOS VCO using optimised hollow spiral inductors



From: J. Craninckx and M. S. J. Steyaert, "**A 1.8-GHz Low-Phase-Noise CMOS VCO Using Optimized Hollow Spiral Inductors**," *IEEE Journal of Solid-state Circuits*, vol. 32, no. 5, May 1997 (pp. 736-744).

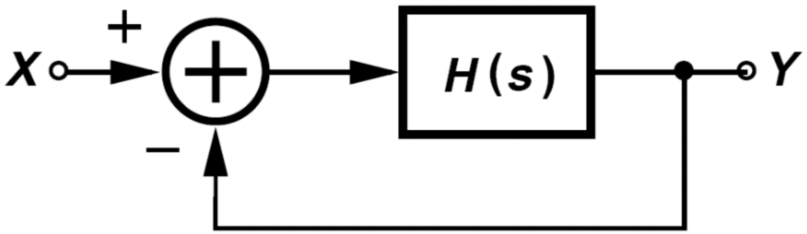
- How can we understand such a **voltage-controlled oscillator** (**VCO**) circuit from the basic concepts?
- Why is it designed in such a way? What topology is it?

Xi'an Jiaotong-Liverpool University 西交利物浦大學

Oscillators

(feedback system)

- An **oscillator** can be described by a positive (or **regenerative**) **feedback** system.
  - In **regenerative feedback**, a portion of the output signal is fed back to the input and it is in phase with the input signal.
- Consider a negative feedback system,



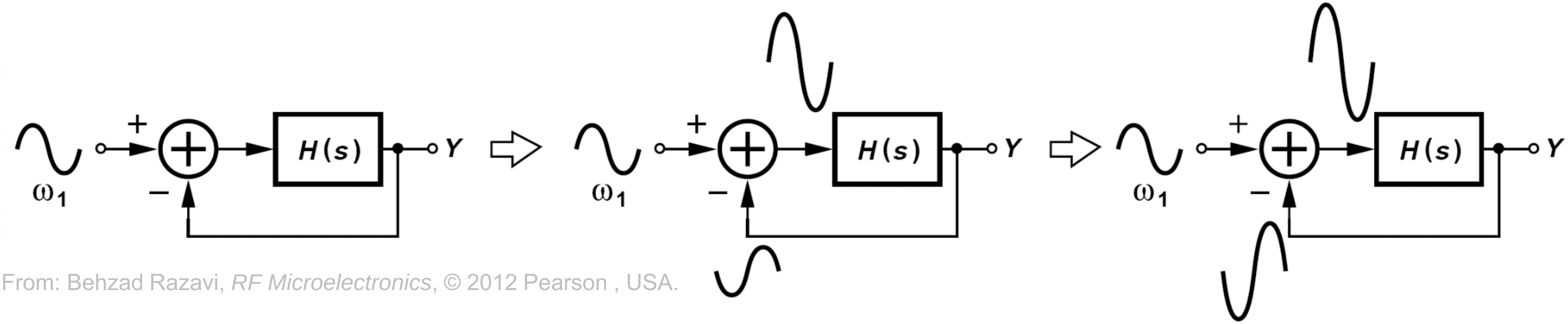
$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{V_Y(s)}{V_X(s)} = \frac{H(s)}{1+H(s)}$$

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

Oscillation in Feedback System

(at a particular frequency)

- In a negative feedback system, if for $s = j\omega_1$, the open-loop transfer function $H(j\omega_1) = -1$, then the closed-loop gain approaches infinity at ω_1.
  - The system can amplify its own noise component at ω_1 indefinitely. $\dfrac{V_{out}(j\omega_1)}{V_{in}(j\omega_1)} = \dfrac{H(j\omega_1)}{1+H(j\omega_1)} \rightarrow \dfrac{-1}{1+(-1)} \rightarrow \infty$



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

  - Will the output get to infinity? Why not?

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Oscillation in Feedback System

(Barkhausen criteria)

- Called "**Barkhausen criteria**", two conditions are necessary (but not sufficient) for a negative feedback system to oscillate:

$$|H(j\omega_1)| \geq 1 \text{ and } \angle H(j\omega_1) = 180^\circ$$

  - These two criteria state that the phase shift at ω_1 around the feedback loop must be 0° or 360° (i.e. positive feedback) and the loop gain must be no less than unity.

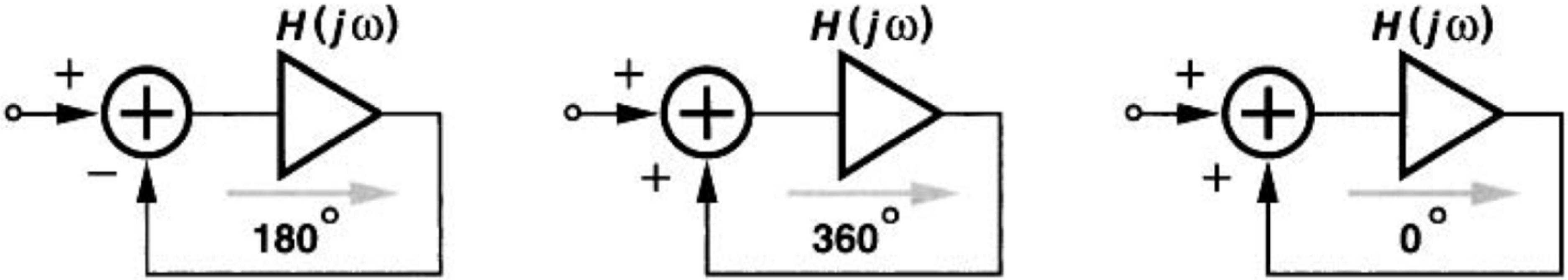
- To ensure oscillation due to temperature or process variations, a loop gain of at least twice or three times the required value is needed.

Xi'an Jiaotong-Liverpool University
西交利物浦大學

Oscillation in Feedback System

(phase shift condition)

- The second "**Barkhausen criterion**" $\angle H(j\omega_1) = 180°$ can be stated in two other equivalent ways:



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

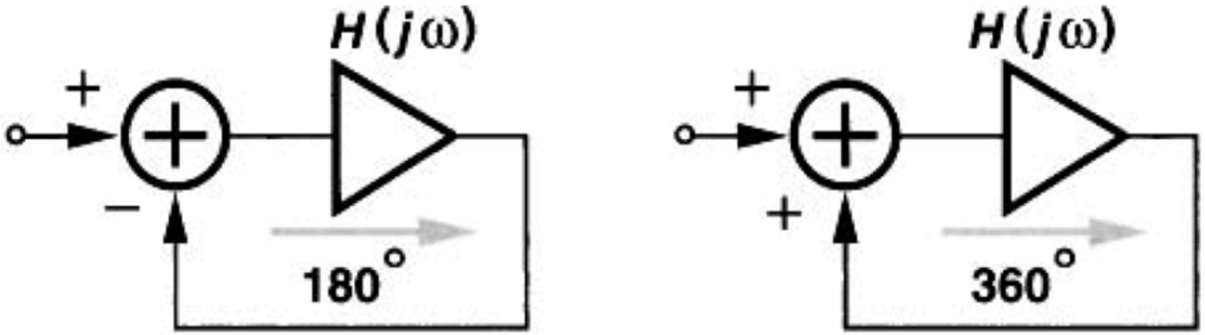
- Note that in a negative feedback system, the **phase shift** is already 180° in the signal travelling around the loop (as represented by the subtraction sign). This is called the DC or low-frequency phase shift of 180°.
- $\angle H(j\omega_1) = 180°$ refers to the ***frequency-dependent*** **phase shift**.

Xi'an Jiaotong-Liverpool University
西交利物浦大學

Oscillation in Feedback System

(360° phase shift)

- The second "**Barkhausen criterion**" $\angle H(j\omega_1) = 180°$ can be stated in two other equivalent ways:



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

- The total phase shift is 360° at particular frequencies in the whole feedback system. This can be achieved by having enough stages with proper polarities to provide the total phase shift of 360°.

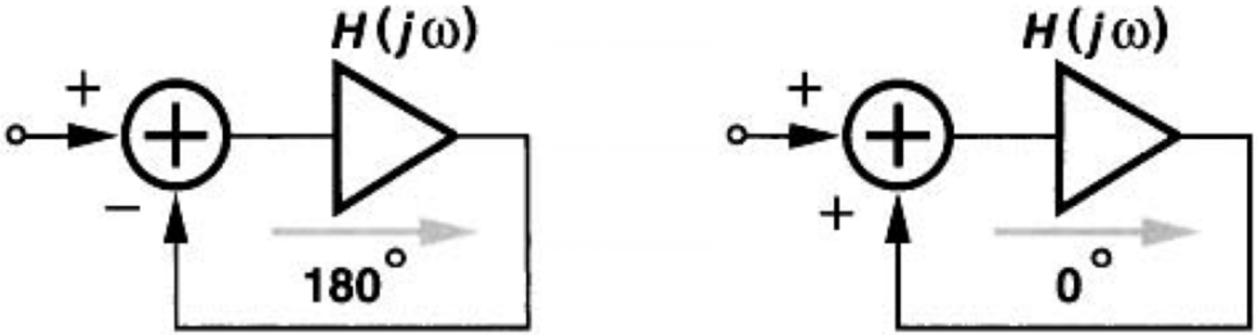
  $\Rightarrow$ ring oscillators

Xi'an Jiaotong-Liverpool University 西交利物浦大学

Oscillation in Feedback System

(0° phase shift)

- The second "**Barkhausen criterion**" $\angle H(j\omega_1) = 180°$ can be stated in two other equivalent ways:



From: Behzad Razavi, *Design of Integrated Circuits for Optical Communications*, 2e © 2012 Wiley, USA.

  - The whole feedback system produces no phase shift (i.e. 0°) at a particular frequency ω. This implies very few gain stages $\Rightarrow$ cross-coupled stages.

Positive Feedback for Oscillation

(oscillators built from op amp)

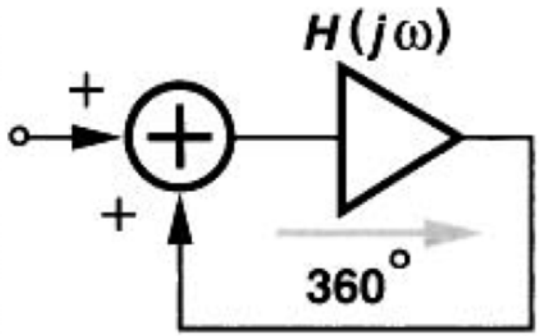
- The main idea of constructing an oscillatory electronic circuit is **positive feedback** using certain gain stages.
- In principle, **operational amplifiers** (**op amp**) can be used to build oscillators. They are not commonly used in RF circuits.
  - Op-amp-based oscillators can be used to generate signals with frequencies of up to approximately one-half of the gain-bandwidth product (ω_{GX}) of the op amp.
  - Oscillators designed with transistors and inductors and capacitors can generate signals with frequencies limited only by the cut-off frequency of the individual transistors.

Xi'an Jiaotong-Liverpool University 西交利物浦大学

Oscillation in Feedback System

(360° phase shift)

- To achieve oscillation, we may cascade multiple gain stages so that the phase shift of individual gain stages would add up to 360°.



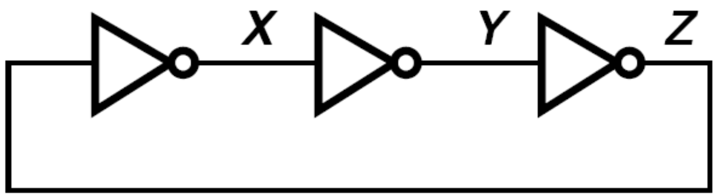
  - Note that in op amp design, cascading "too many" gain stages for a very large signal gain is undesirable because this would cause instability.

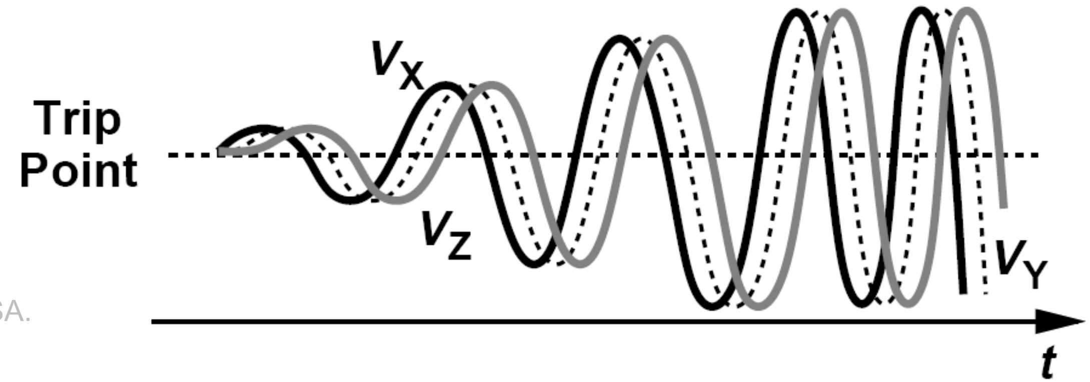
- This is the **ring oscillator** design approach.
- A **ring oscillator** consists of a number of **gain stages** in a **loop**.

Ring Oscillators

(cascading odd number of inverters)

- ❑ A simple implementation of a **ring oscillator** is cascading an odd number of the inverter logic gates in a loop.
  - ➢ Why odd number (typically no less than three)?
  - ➢ Such a ring oscillator is helpful in determining the maximum speed of the logic gates in an IC technology.





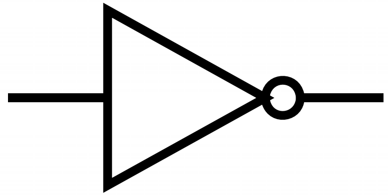
From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

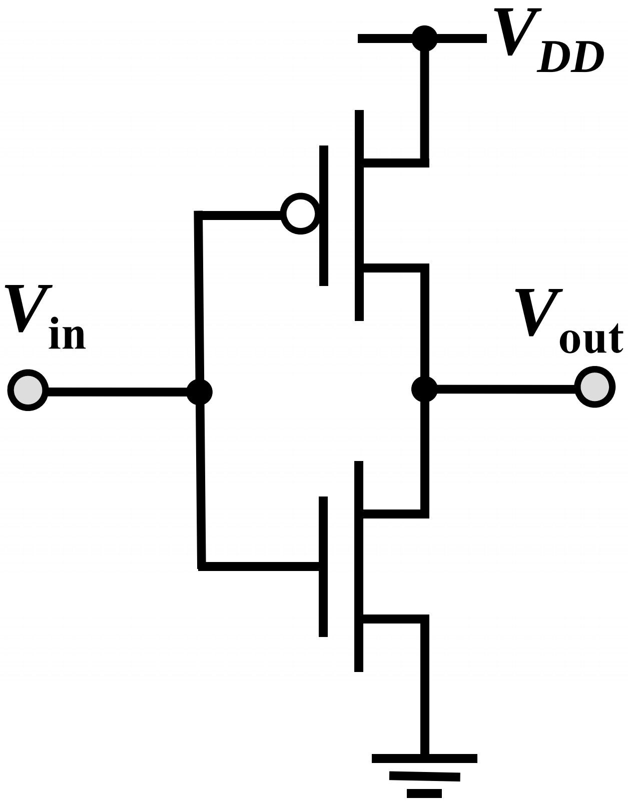
- ➢ How to estimate the oscillation frequency from the inverter delay?

Ring Oscillators

(CMOS inverter)

- In CMOS technology, an efficient **inverter** logic gate can be constructed with one ***n***-channel MOSFET and one ***p***-channel MOSFET.





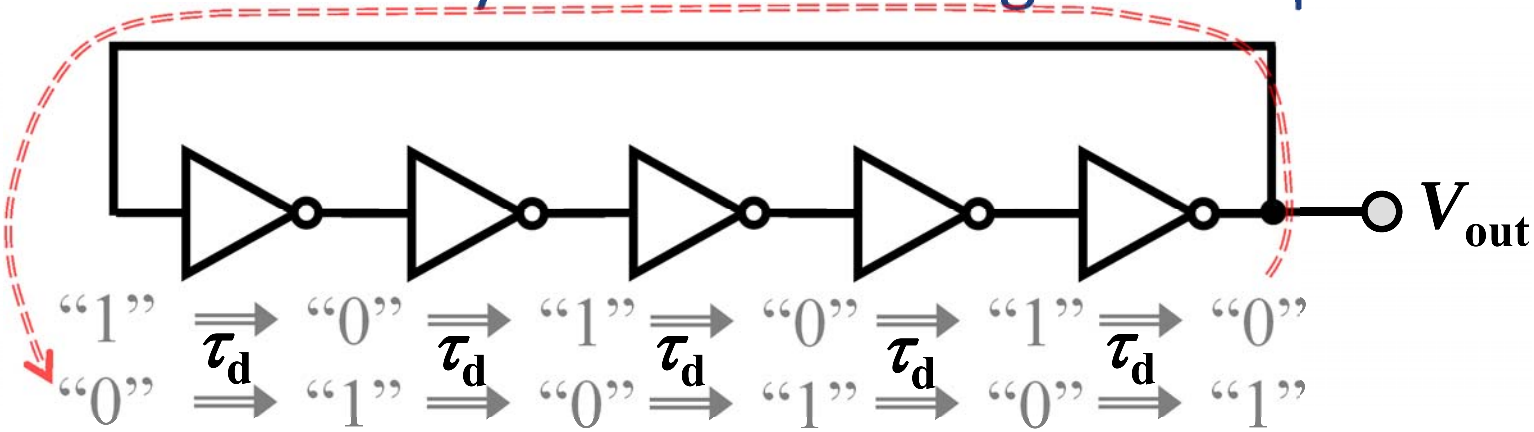
- Do you still remember what you learned in EEE112 & EEE201 in designing W/L and estimating the **delay time** of a CMOS inverter?
  - If the delay of an inverter is 0.2 ns, what is the oscillation frequency of a 5-inverter ring oscillator?

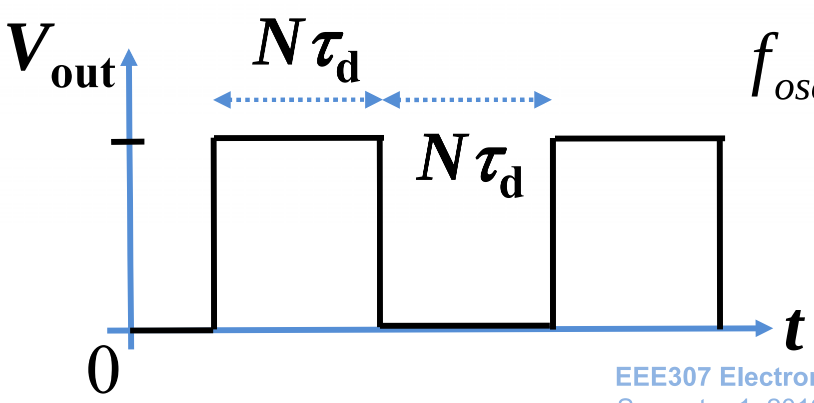
Xi'an Jiaotong-Liverpool University 西交利物浦大學

Ring Oscillators

(inverter delay & oscillation frequency)

- With the odd number of the inverter logic gates in a loop, the output would be fed back to the input after the delay time and change the input:





$$f_{osc} = \frac{1}{T} = \frac{1}{2N\tau_d}$$

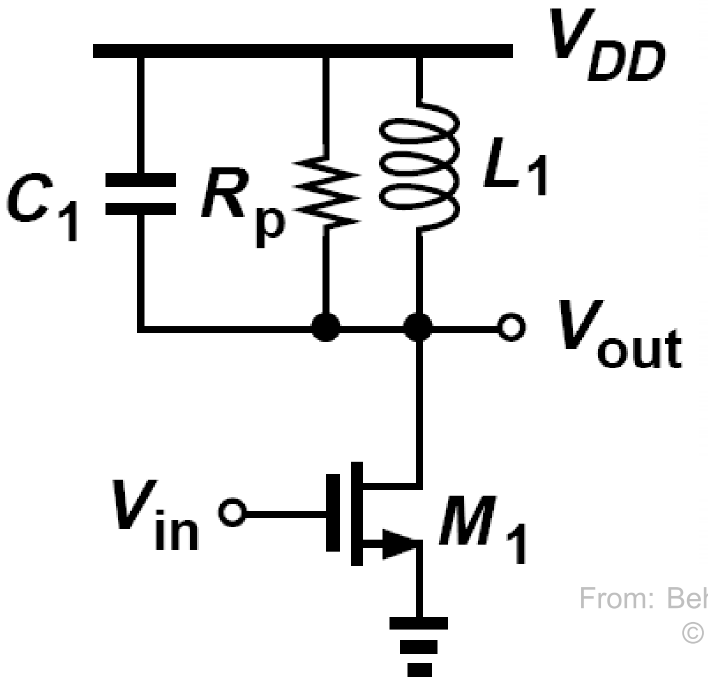
τ_d: inverter delay

N: odd number of inverters

Oscillators from Tuned Amplifiers

(using inductors & capacitors)

- In RF circuits, it is more common to construct an **oscillator** circuit from a ***tuned*** **amplifier** using inductors and capacitors.
  - In a common-source amplifier, $\dfrac{V_{out}}{V_{in}} = -g_m\left(X_C \,//\, R_p \,//\, X_L \,//\, r_{o1}\right)$



  - At low frequencies, $\dfrac{V_{out}(s)}{V_{in}(s)} \approx -g_m s L_1$
  - At ω_0, $\dfrac{V_{out}(j\omega_0)}{V_{in}(j\omega_0)} \approx -g_m R_p$
  - At high frequencies, $\dfrac{V_{out}(s)}{V_{in}(s)} \approx -\dfrac{g_m}{sC_1}$

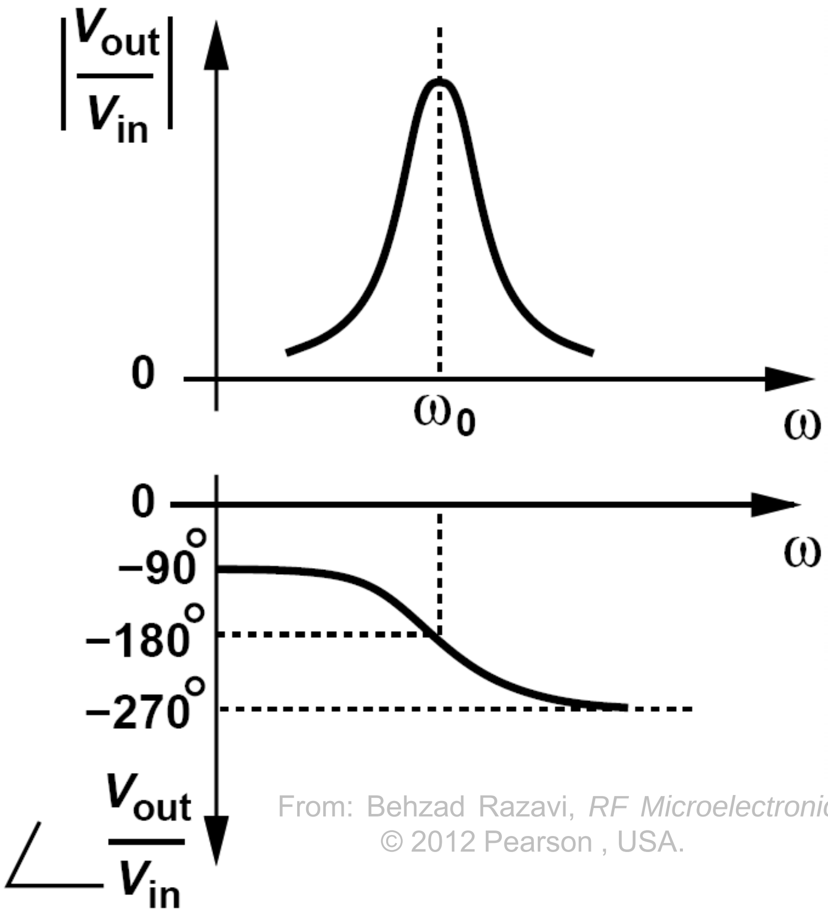
From: Behzad Razavi, *RF Microelectronics*,

Xi'an Jiaotong-Liverpool University 西交利物浦大学

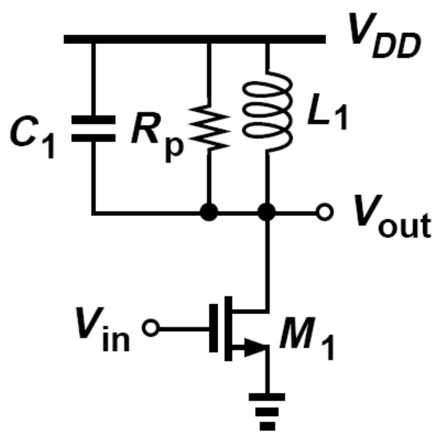
LC-Tuned Amplifier

(phase shift at different frequencies)

- The LC-tuned amplifier can achieve the required phase shift for oscillation at a particular frequency.
  - At low frequencies, the phase shift is $\angle(V_{out}/V_{in}) \approx$ -90°. (Why?)
  - At very high frequencies, the phase shift is $\angle(V_{out}/V_{in}) \approx$ +90°. (Why?)
  - At the resonance frequency ω_0, the phase shift from the input to the output is 180°.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.



Xi'an Jiaotong-Liverpool University 西交利物浦大学

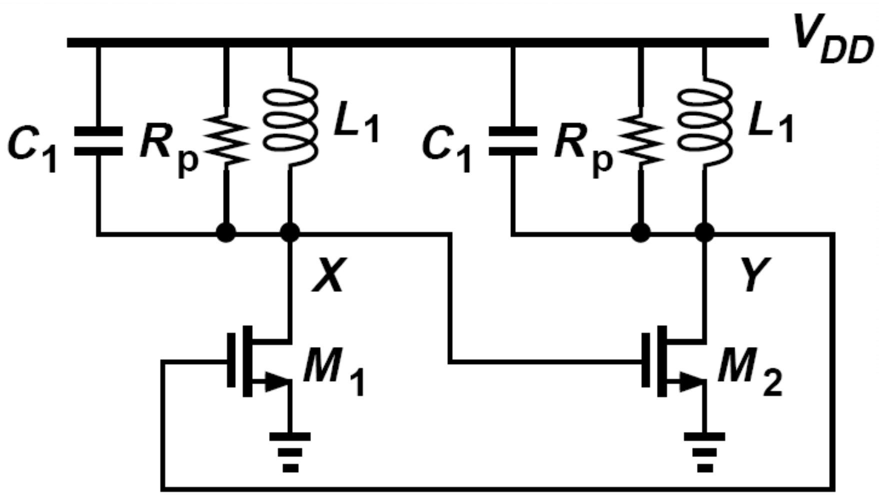
LC-Tuned Amplifier

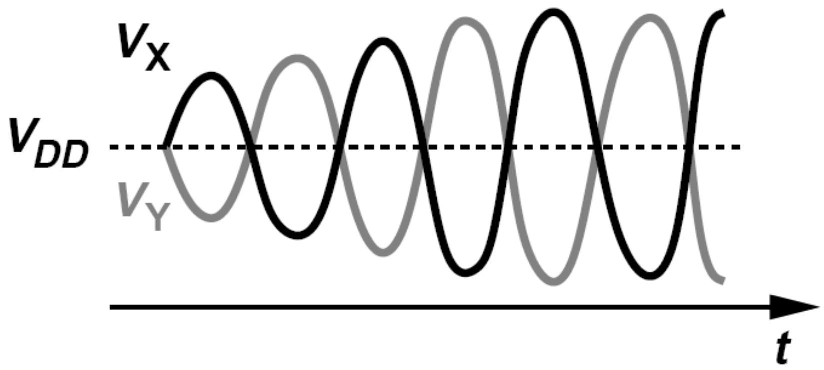
(cascading two CS amplifiers)

- With the 180° phase shift at the resonance frequency ω_0 of the LC-tuned amplifier, ***cascading*** two **common-source amplifier** in a loop will form an **oscillator** with the positive (regenerative) feedback.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

  - The circuit oscillates if the loop gain $(g_m R_p)^2 \geq 1$.



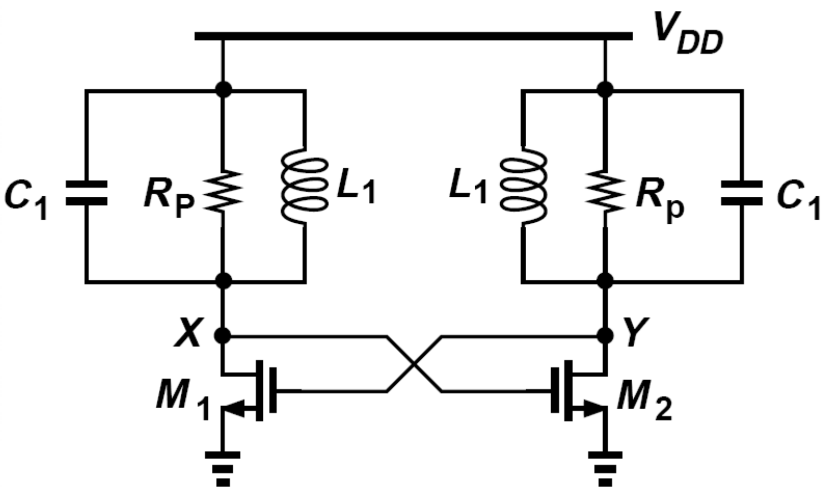


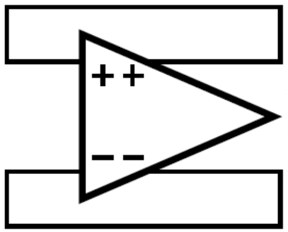
Cross-Coupled LC Oscillators

(two amplifiers with positive feedback)

- ❑ The **oscillator** circuit with two common-source amplifiers ***cascaded*** in a **loop** can be represented in a different form.
- ❑ This is the dominant **cross-coupled LC oscillator** design for RF applications due to its robust operation.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.





- ➢ It is like a differential amplifier with the outputs fed into the inputs in phase.
- ➢ Note that resonance frequency ω_{osc} can include the parasitic capacitances of the transistors.

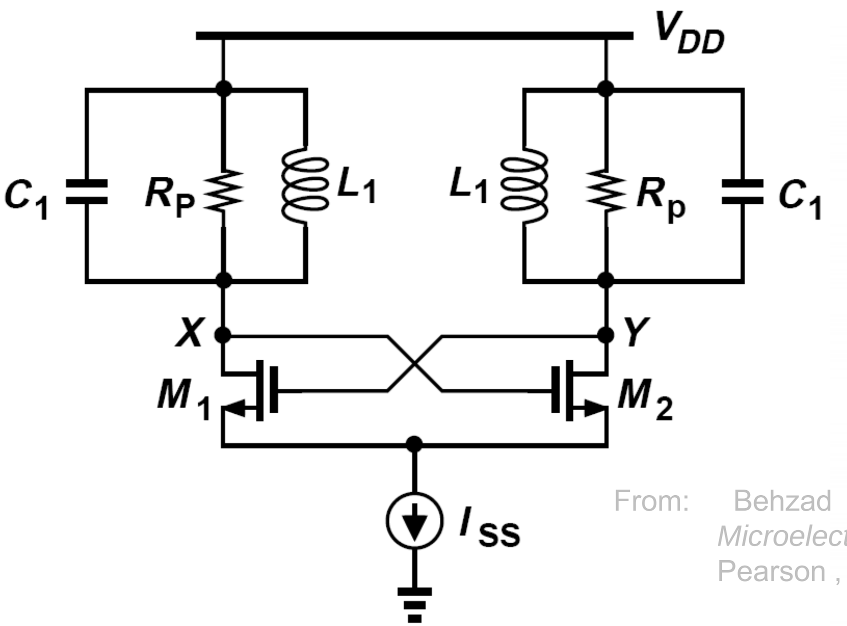
$$\omega_{osc} = \frac{1}{\sqrt{L_1(C_{GS2} + C_{DB1} + 4C_{GD} + C_1)}}$$

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Cross-Coupled LC Oscillators

(two amplifiers with positive feedback)

- The **cross-coupled LC oscillator** design can have the differential pair of transistors biased with a certain DC current I_{SS}.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

- Then the DC offset voltage V_{XY} at the differential output can be set at such a value so that the output **voltage swing** can be maximised.

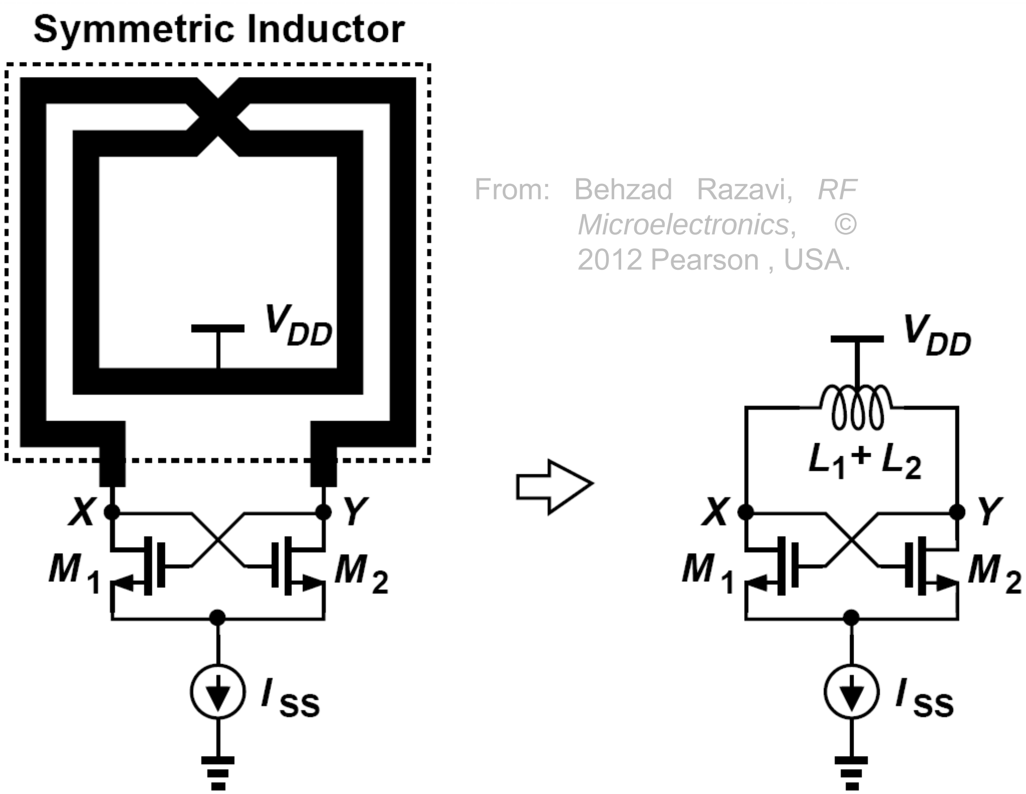
$$V_{XY} \approx \frac{4}{\pi} I_{SS} R_p$$

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

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Cross-Coupled LC Oscillators
(symmetric spiral inductors)

- The **cross-coupled LC oscillator** gives a differential output. A symmetric planar spiral inductor can be used in RFIC design for improved performance.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

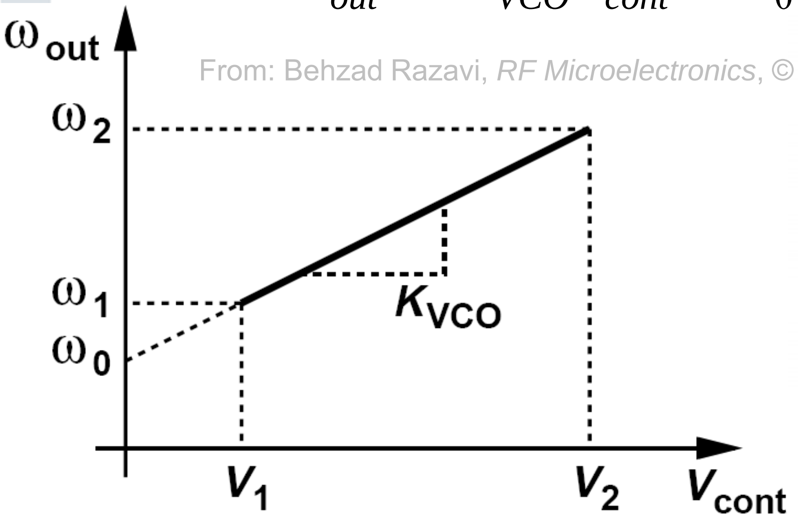
- The point of symmetry of the planar spiral inductors, namely the “centre tap” is connected to V_{DD}.

Voltage-Controlled Oscillator

(varying frequency by voltage)

- In most applications, **oscillators** need to be tuned over a certain frequency range.
- Typically, the frequency is varied electronically by a controlling voltage. Such a oscillator is called **voltage-controlled oscillator (VCO)**.

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



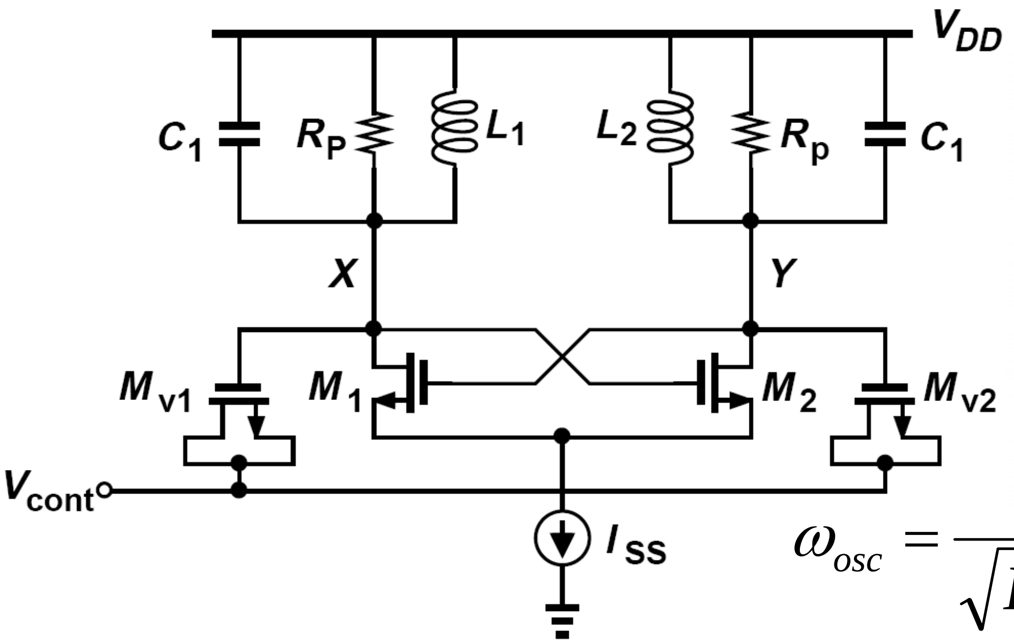
- K_{VCO} is ideally a constant and is called the "gain" or "sensitivity" of the VCO and is expressed in radian/Hz/V.

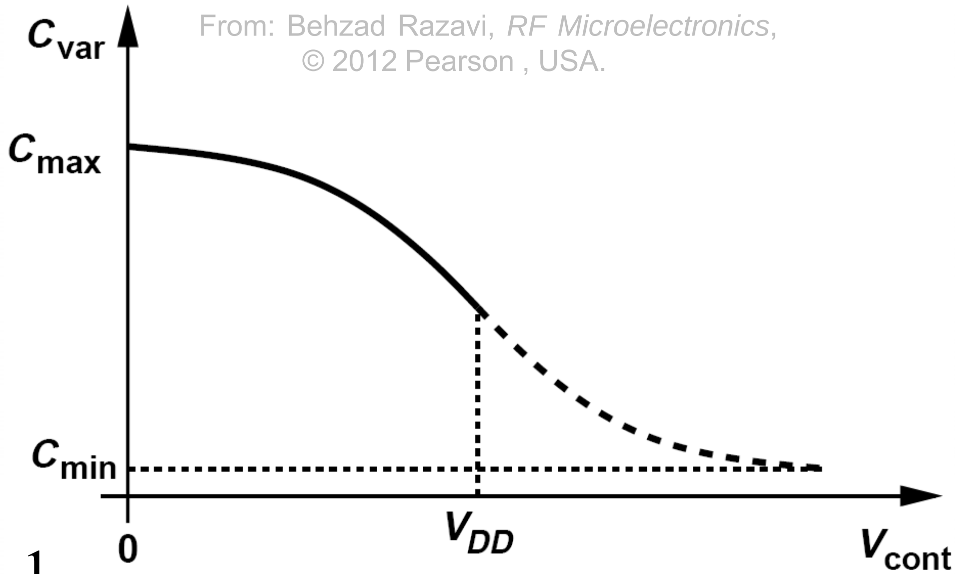
Xi'an Jiaotong-Liverpool University 西交利物浦大学

Voltage-Controlled Oscillator

(use of varactors)

- The **cross-coupled LC oscillator** can be made into a VCO easily by adding a device called **varactor**.
  - A **varactor** changes its capacitance with an applied voltage. A **MOS capacitor** can serve as a **varactor** by tying the source and drain.





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

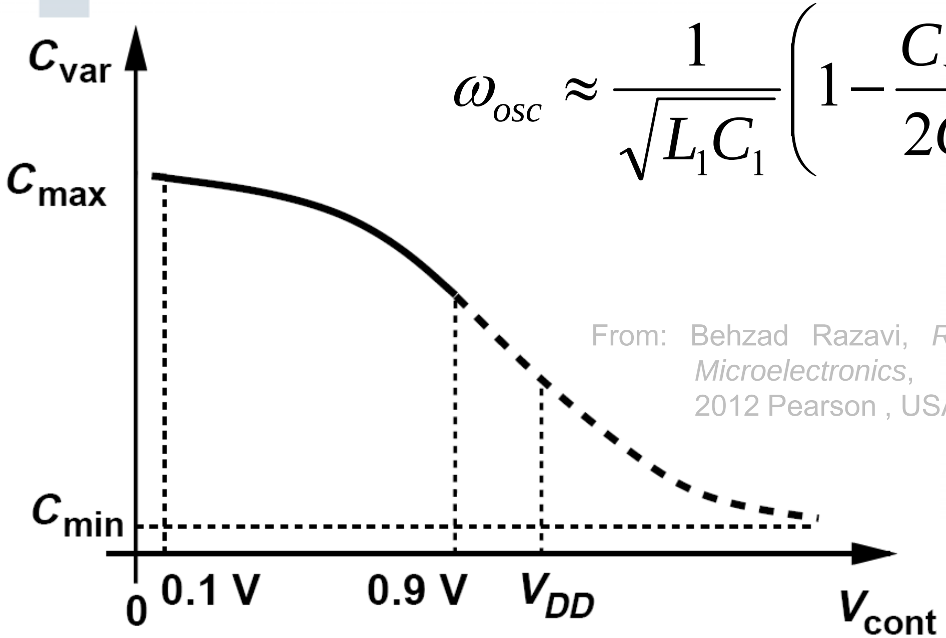
Voltage-Controlled Oscillator

(frequency tuning range)

- With the varactor's capacitance included in the resonance frequency, the oscillator's frequency ω_{osc} becomes:

$$\omega_{osc} = \frac{1}{\sqrt{L_1 C_1 (1 + C_{\text{var}} / C_1)}} = \frac{1}{\sqrt{L_1 C_1}} \left(1 + \frac{C_{\text{var}}}{C_1}\right)^{-\frac{1}{2}}$$

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



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

  - The frequency tuning range of the VCO is

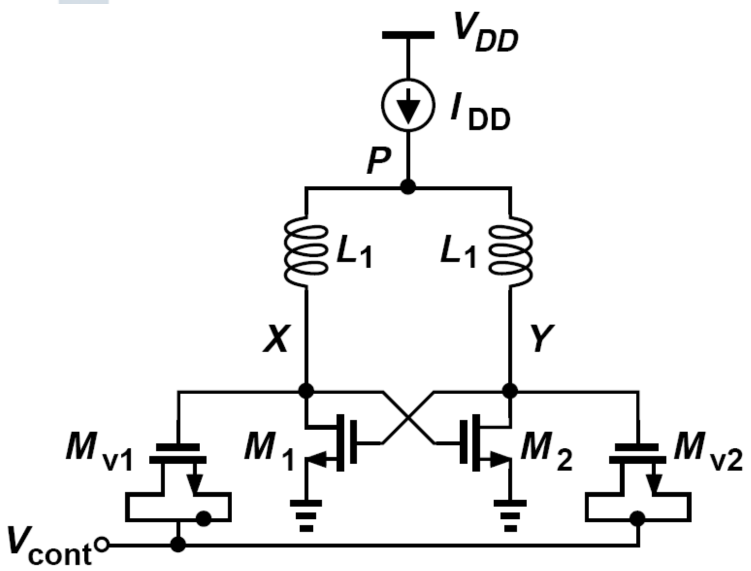
$$\Delta\omega_{osc} \approx \frac{1}{\sqrt{L_1 C_1}} \left(\frac{C_{\text{var}2} - C_{\text{var}1}}{2C_1}\right)$$

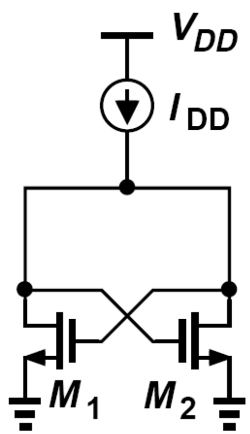
Xi'an Jiaotong-Liverpool University 西交利物浦大学

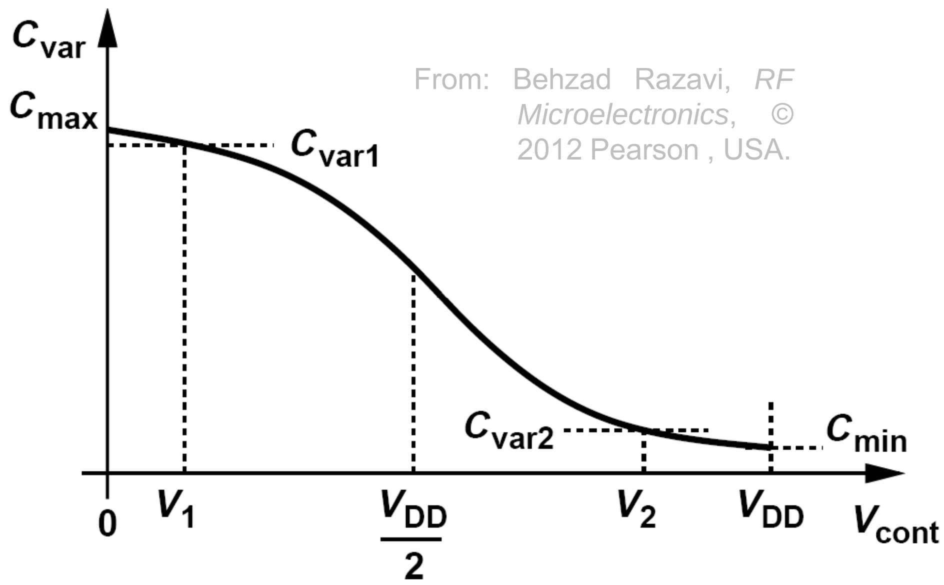
Voltage-Controlled Oscillator

(frequency tuning range improvement)

- In using the MOS capacitor as a varactor in the **cross-coupled LC oscillator**, the frequency <u>tuning range</u> can be increased by using a top current source (compared with the tail-biased circuit).







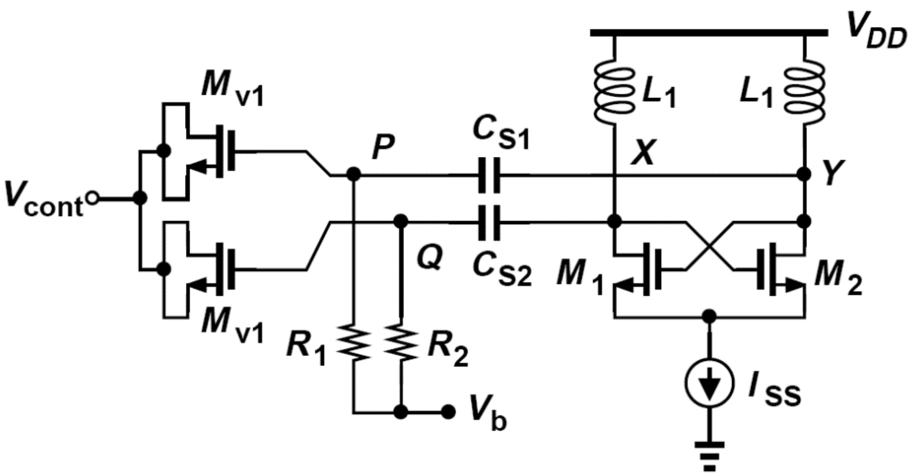
From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

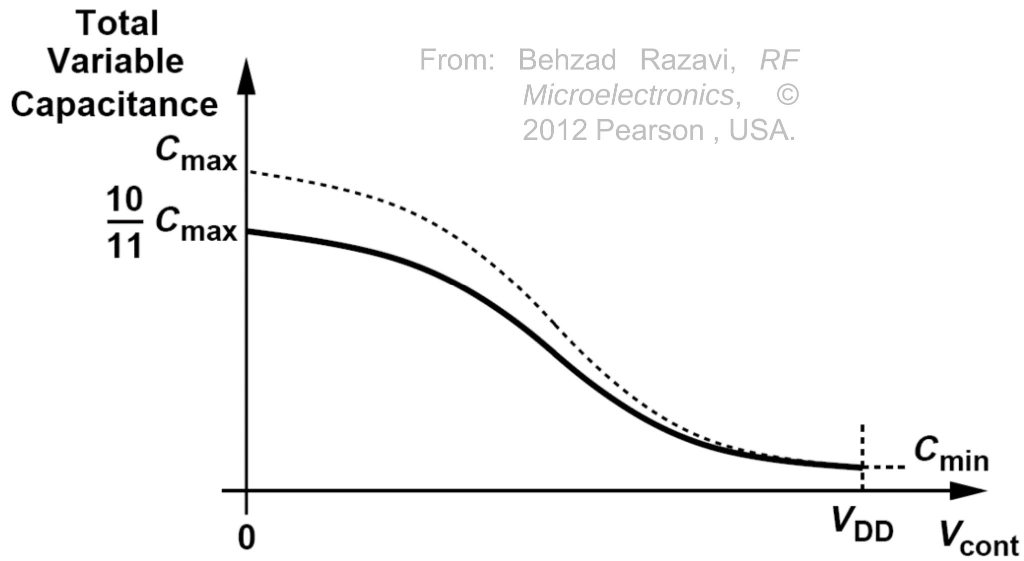
- This however suffers from worse phase noise.

Voltage-Controlled Oscillator

(varactor AC coupling)

- There can be varactor modulation in the **cross-coupled LC oscillator** due to the noise of the bias current source.
- This can be avoided by using AC coupling between the varactors and the core (i.e. connecting the varactors to the transistor core through linear capacitors).





From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

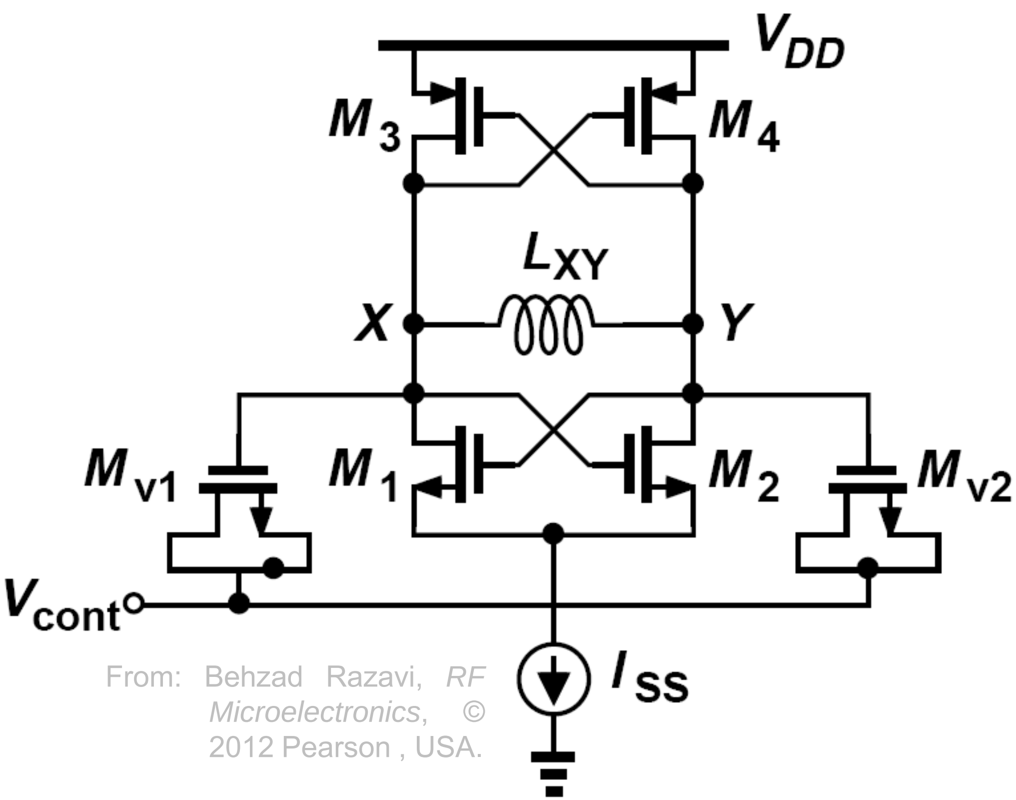
➢ Disadvantage: less tuning range

Xi'an Jiaotong-Liverpool University 西交利物浦大学

Voltage-Controlled Oscillator

(cross-coupled PMOS transistor)

- Another improvement of the **cross-coupled LC oscillator** is the use of cross-coupled PMOS transistors to replace the resistors.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

- With proper choices of the MOSFET size (i.e. W/L) and the biasing current I_{SS}, the common mode voltage at nodes ***X*** and ***Y*** can be set at $V_{DD}/2$ and hence increasing the VCO output voltage swing, specifically doubled.

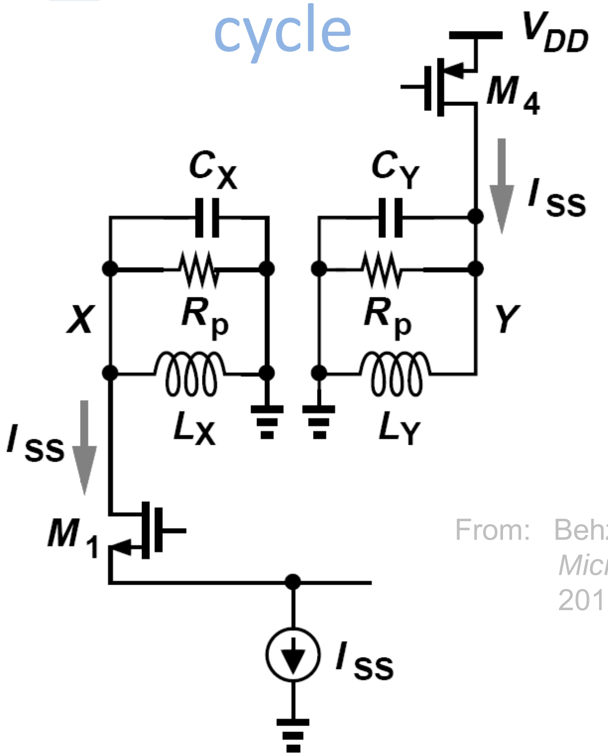
Xi'an Jiaotong-Liverpool University 西交利物浦大学

VCO with Cross-Coupled PMOS

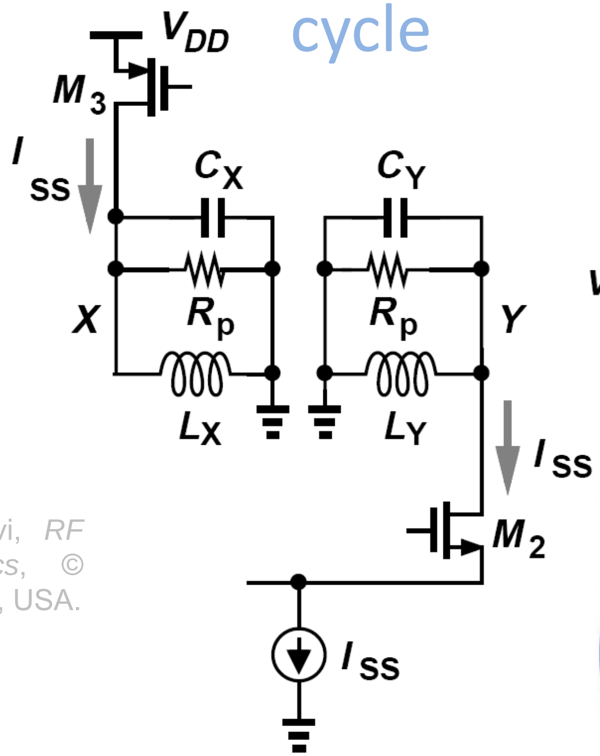
(operation)

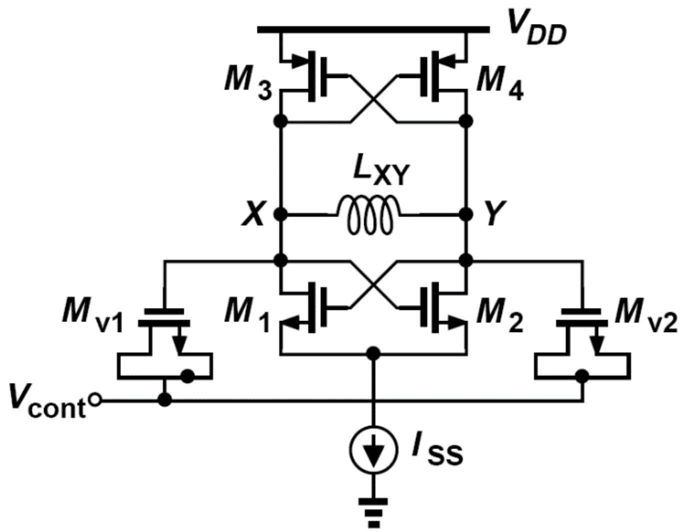
- The operation of the **cross-coupled LC oscillator** with **cross-coupled PMOS transistors** can be understood by looking at the current flow in each half cycle of the VCO.

1st half cycle



2nd half cycle



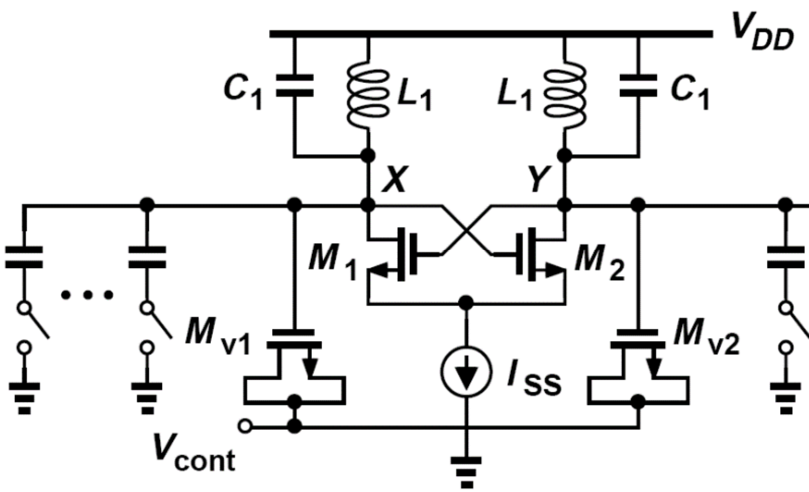


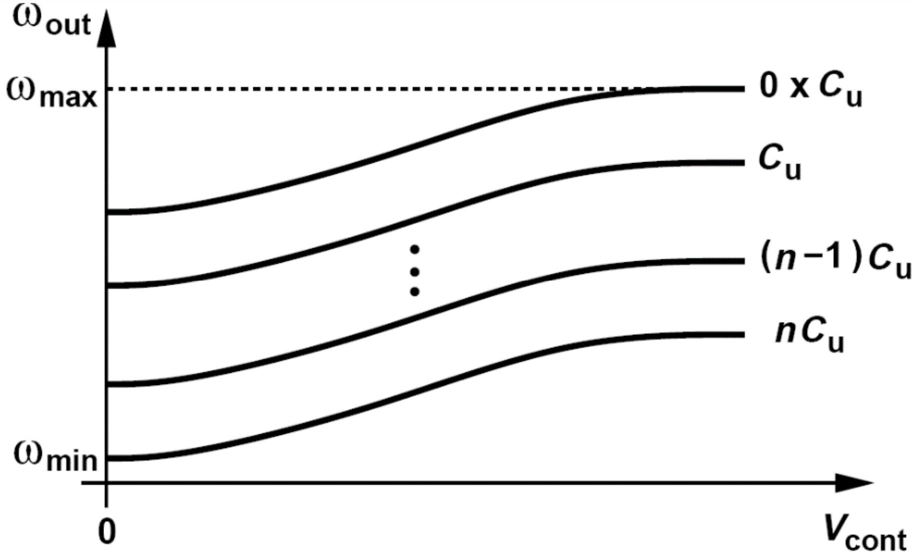
From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Voltage-Controlled Oscillator
(discrete tuning)

- In the **cross-coupled LC oscillator** design, discrete tuning range is possible by adding a bank of small capacitors (e.g. parallel-plate capacitors) in parallel to the LC tanks.
  - The capacitors can be switched in or out to adjust the resonance frequency ω_{osc}.





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

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

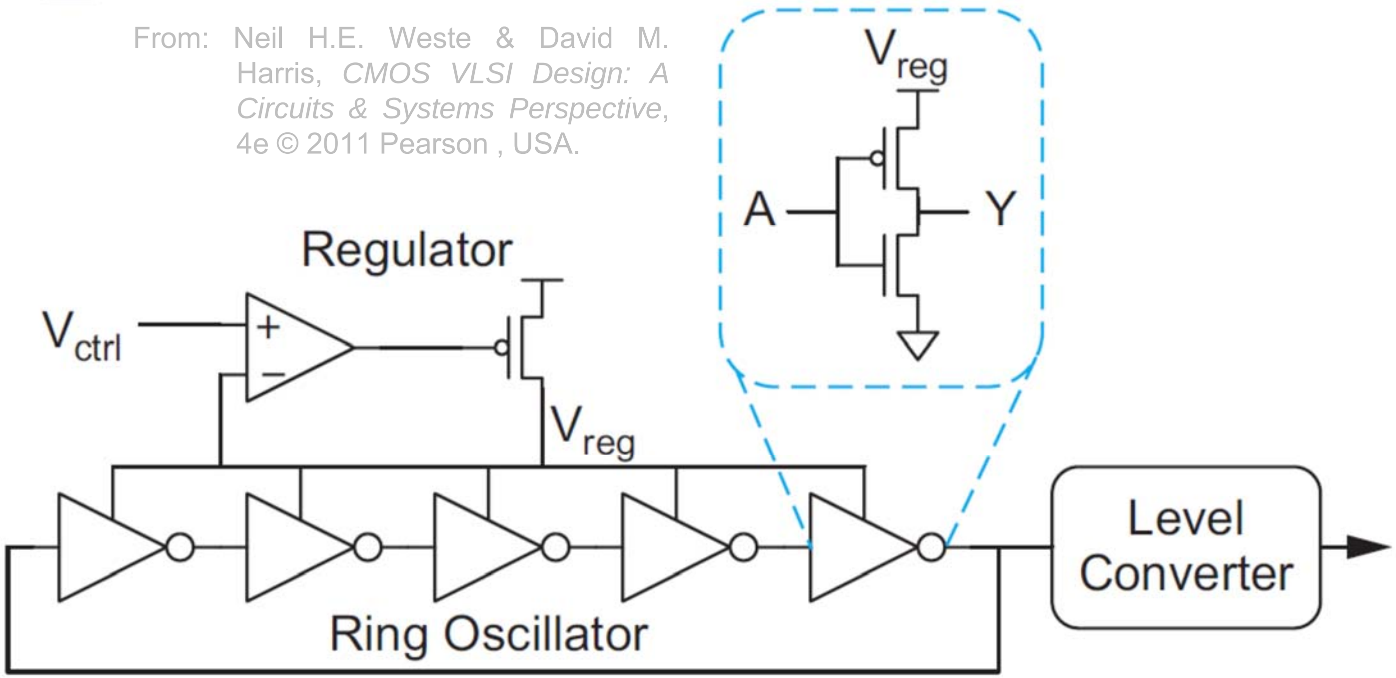
Xi'an Jiaotong-Liverpool University 西交利物浦大学

Voltage-Controlled Oscillator

(ring oscillator)

- ❑ The **ring oscillator** design can also be made as a VCO.
- ❑ The oscillation frequency can be controlled by the **delay** of each inverter stage.

From: Neil H.E. Weste & David M. Harris, *CMOS VLSI Design: A Circuits & Systems Perspective*, 4e © 2011 Pearson , USA.



- ➢ The delay of each inverter stage can be controlled by the supply voltage hence the dynamic current.
- ➢ A level converter restores the output to the full swing of the supply voltage.

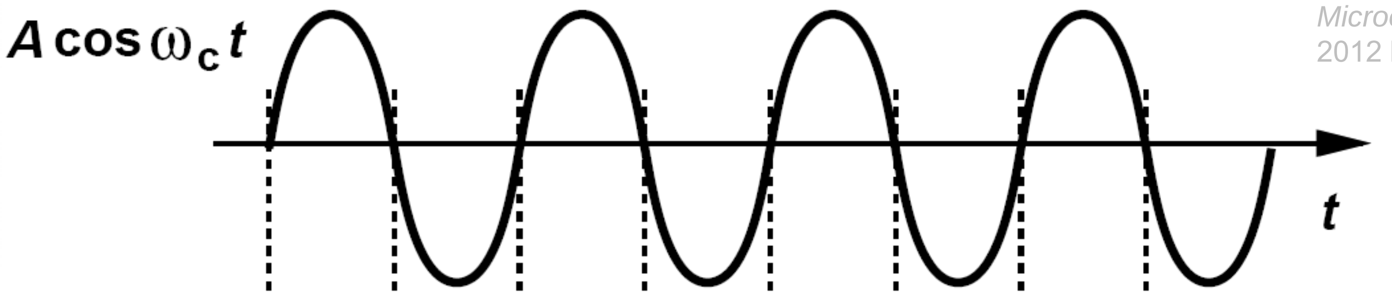
Xi'an Jiaotong-Liverpool University
西交利物浦大学

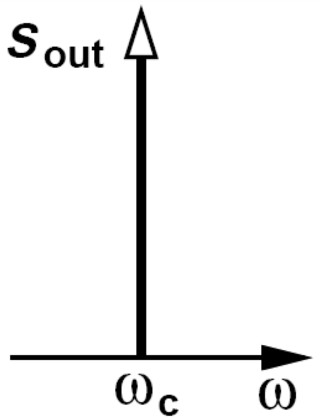
Phase Noise of VCO

(ideal oscillator)

- An ideal **oscillator** produces a perfectly periodic output of the form $v(t) = A\cos(\omega_c t)$.
- The zero crossings occur at exact multiples of the period ($T_c = 2\pi/\omega_c$) of the waveform.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.





- In the frequency spectrum, it would ideally consist of one impulse at ω_c.

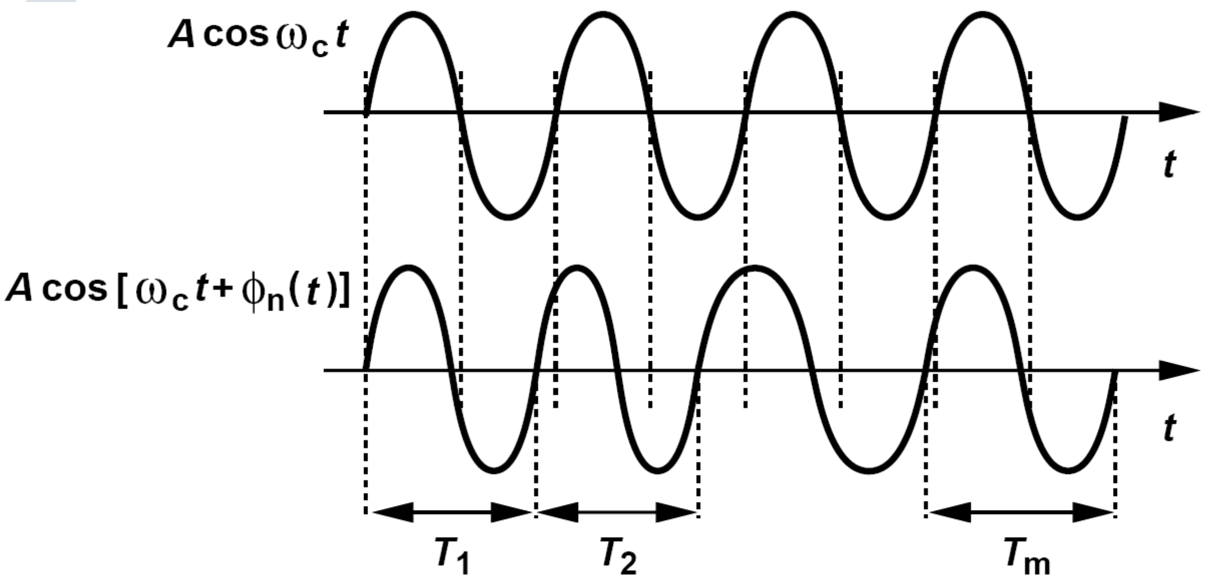
Xi'an Jiaotong-Liverpool University
西交利物浦大学

Phase Noise of VCO

(perturbed zero crossings)

- In reality however, the noise of the oscillator randomly ***perturbs*** the **zero crossings**.
  - To model this perturbation, we can write $v(t) = A\cos(\omega_c t + \phi_n(t))$, where $\phi_n(t)$ is a small ***random*** **phase** quantity that ***deviates*** the **zero crossings** from integer multiples of T_c.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.



- $\phi_n(t)$ is called the **phase noise** of the oscillator. This is viewed in the time domain.

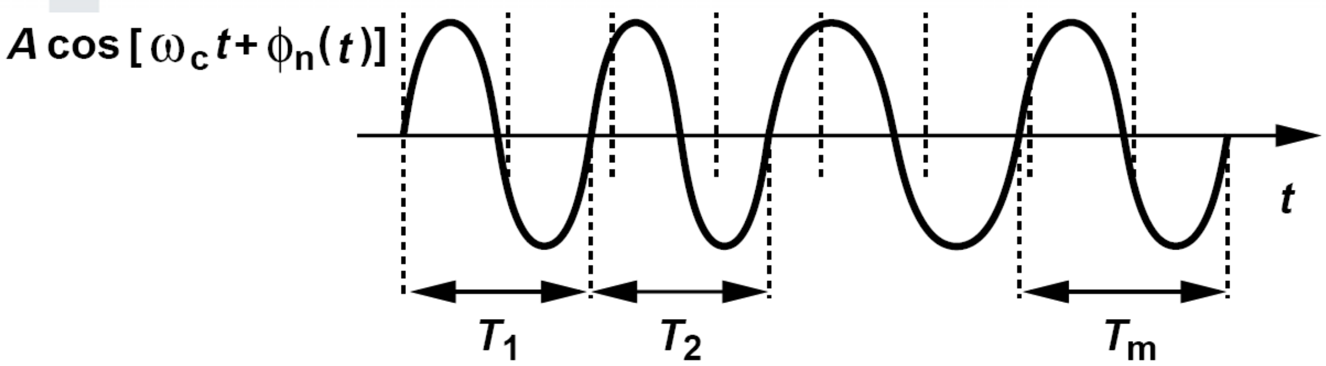
Xi'an Jiaotong-Liverpool University 西交利物浦大学

Phase Noise of VCO

(frequency deviations)

- The **perturbation** of the **zero crossings** can be viewed as the **period** of the waveform ***deviates*** randomly from the constant T_c of a ***perfectly periodic*** signal.
- In other words, the waveform has a *distribution* of **periods** (i.e. T_1, T_2, …, T_m) and hence a *distribution* of **frequencies** (i.e. $1/T_1$, $1/T_2$, …, $1/T_m$).

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.



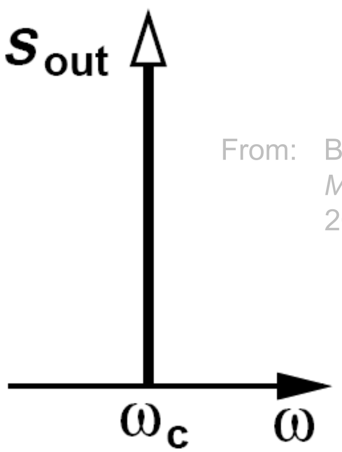
- Note $f_1 = 1/T_1$;
  $\omega_1 = 2\pi/T_1$.

Phase Noise of VCO

(distribution in frequency spectrum)

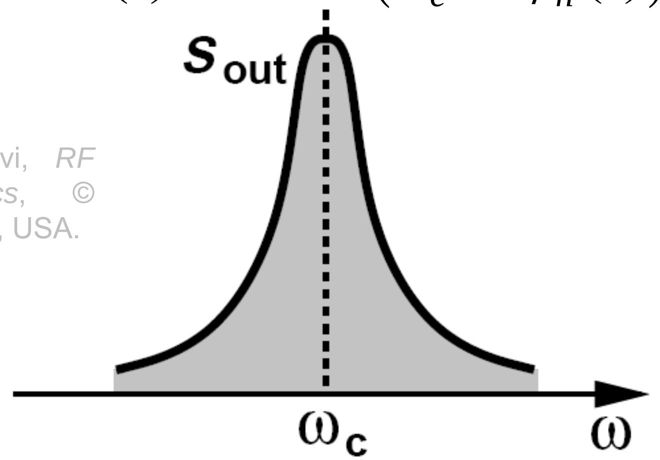
- In the frequency domain, the ***random* deviation** from the constant T_c of a ***perfectly periodic*** signal can be represented by a “broadened” impulse around ω_c.
  - The spectrum of the oscillator output has a ***distribution*** of **frequencies** (ω_1, ω_2, …, ω_m) around ω_c.

$$v(t) = A\cos(\omega_c t)$$



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

$$v(t) = A\cos\left(\omega_c t + \phi_n(t)\right)$$



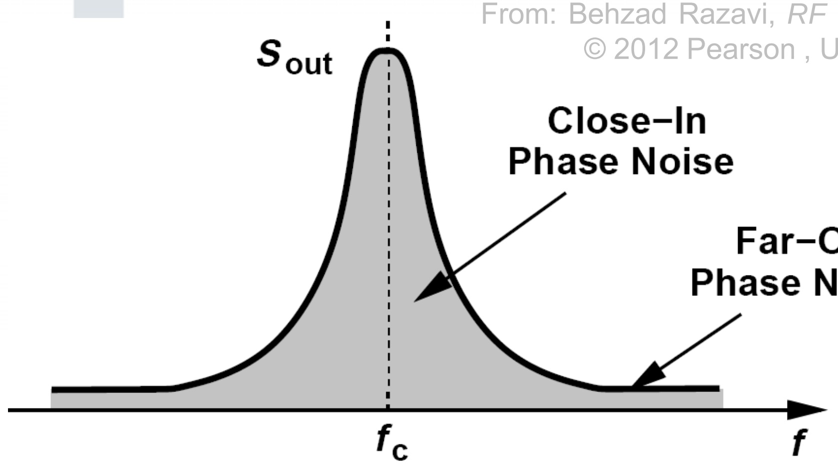
- The frequency deviation from ω_c is due to the random variations of $\phi_n(t)$.

Xi'an Jiaotong-Liverpool University
西交利物浦大学

Phase Noise of VCO

(linkage to time domain)

- The spectrum of the **oscillator** output has declining skirts from the peak at ω_c.
  - The **phase noise** is more significant when it is close to ω_c while it reaches almost a constant floor when the frequency is far away from ω_c.
  - Such behaviour in the frequency domain can be related to the **phase noise** $\phi_n(t)$ in the time domain.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

$$v(t) = A\cos\left(\omega_c t + \phi_n(t)\right)$$
$$\approx A\cos(\omega_c t) - A\sin(\omega_c t)\sin\left(\phi_n(t)\right)$$
$$\approx A\cos(\omega_c t) - \phi_n(t) A\sin(\omega_c t)$$

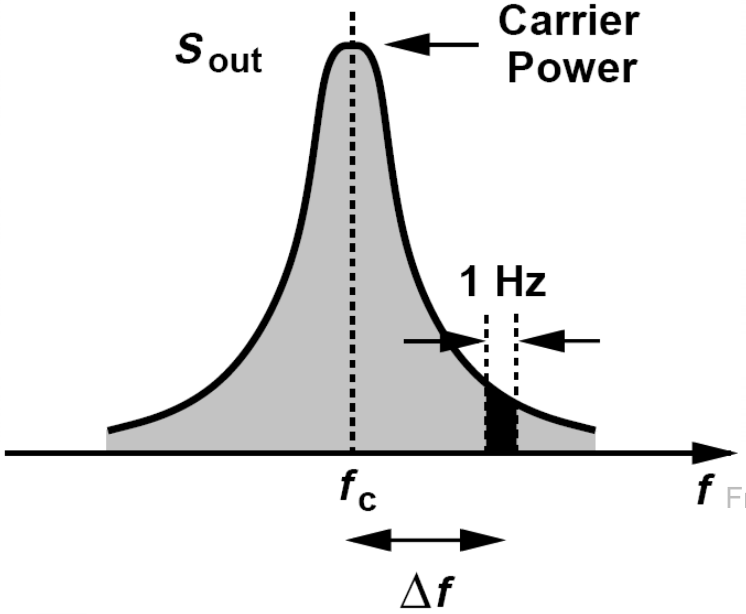
$$\cos(\theta_1 + \theta_2) = \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2$$

$$|\phi_n(t)| << 1 \text{ radian}$$

Phase Noise of VCO

(specifying at offset frequency)

- As the **phase noise** in the frequency domain falls at frequencies farther away from f_c, the **phase noise performance** of an oscillator can be quantified by specifying at a certain **frequency offset** (i.e. a certain difference with respect to f_c).



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

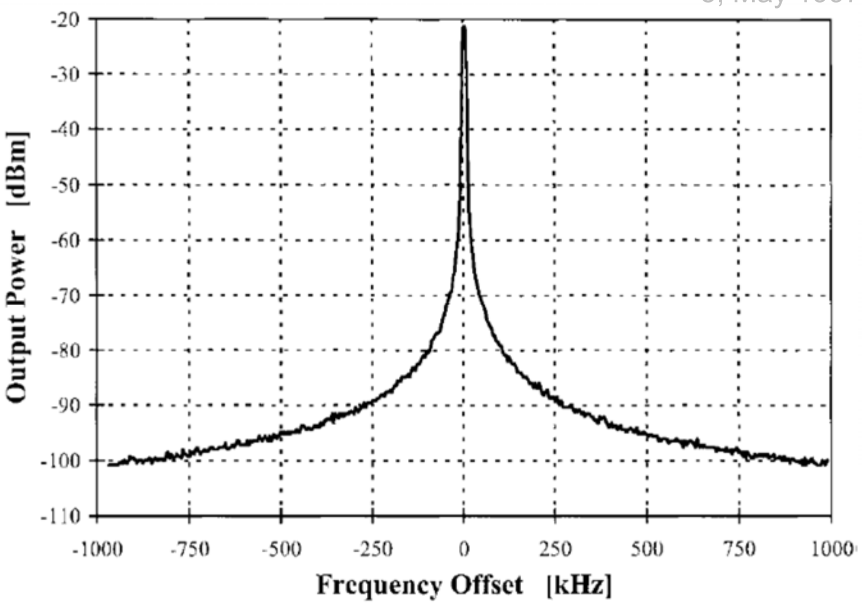
  - We can consider a 1-Hz bandwidth of the spectrum at an offset of Δf and then measure the power in this bandwidth, and finally normalise the power to the "carrier power" (i.e. the peak of the spectrum).

Phase Noise of VCO

(dBc - dB with respect to the carrier)

- As an example in specifying the **phase noise** of an oscillator, the requirement in GSM applications is below -115 **dBc/Hz** at 600-kHz offset.
  - The unit **dBc** is called "**dB with respect to the carrier**" and signifies normalization of the noise power to the carrier power.

From: J. Craninckx and M. S. J. Steyaert, "**A 1.8-GHz Low-Phase-Noise CMOS VCO Using Optimized Hollow Spiral Inductors**," *IEEE Journal of Solid-state Circuits*, vol. 32, no. 5, May 1997 (pp. 736-744).



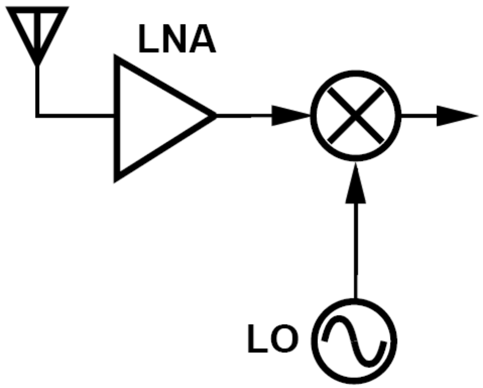
- Can you read the VCO's phase noise here to see if it meets the GSM requirement?
- The phase noise performance is -80 dBc/Hz at 1-MHz offset here.

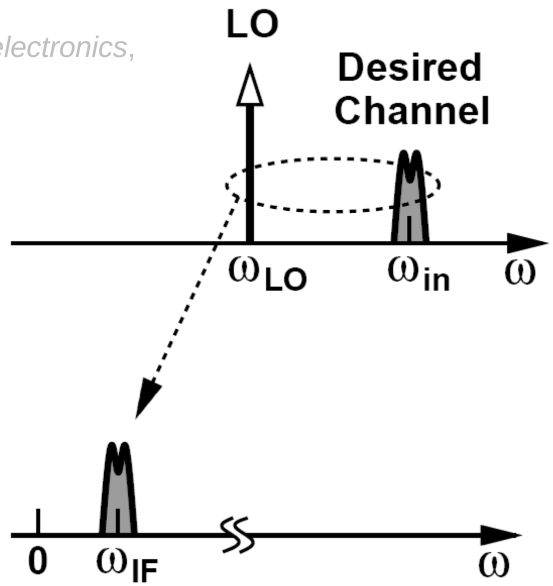
Xi'an Jiaotong-Liverpool University
西交利物浦大学

Phase Noise of VCO

(effect in downconversion)

- The effect of phase noise can be understood in an RF front-end receiver in which the RF signal is downconverted by a mixer driven by a **local oscillator** (LO) signal.
  - With the downconversion mixing, the desired channel is convolved with the impulse at ω_{LO}, producing an intermediate frequency (IF) signal at $\omega_{IF} = |\ \omega_{in} - \omega_{LO}|$.



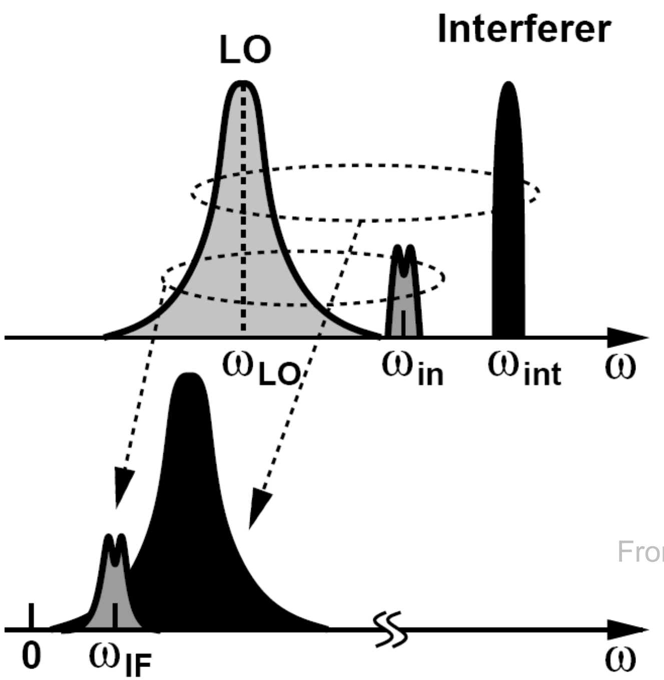


- No problem is caused in the downconversion if the LO signal is **perfectly periodic** (i.e. has <u>no **phase noise**</u>).

Phase Noise of VCO

(effect of downconverted interferer signal)

- It is not uncommon that the desired RF signal is accompanied by a strong interferer signal (and they are close to each other in the frequency spectrum).
- The interferer signal is also downconverted together with the desired RF signal.



- If the LO signal has considerable phase noise, the downconvereted interferer would have its noise skirt corrupting the desired IF signal.
- This phenomenon is called “reciprocal mixing”.

From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.