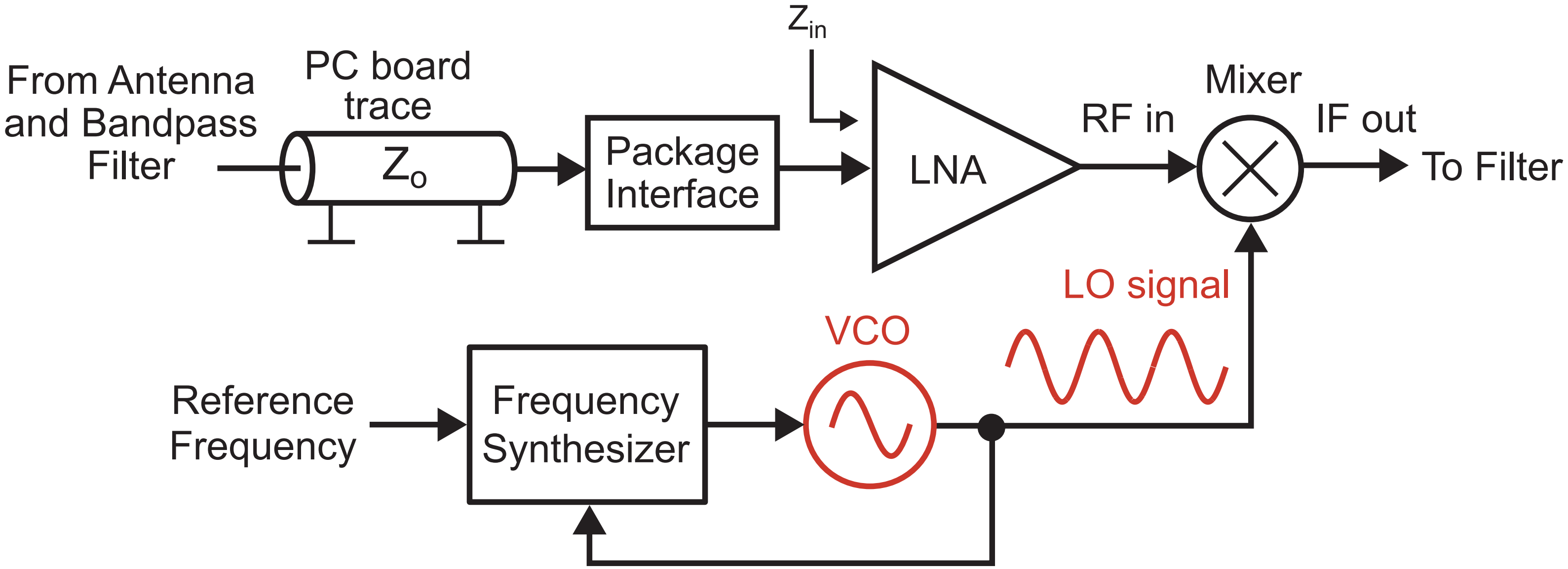
6.976
High Speed Communication Circuits and Systems
Lecture 11
Voltage Controlled Oscillators

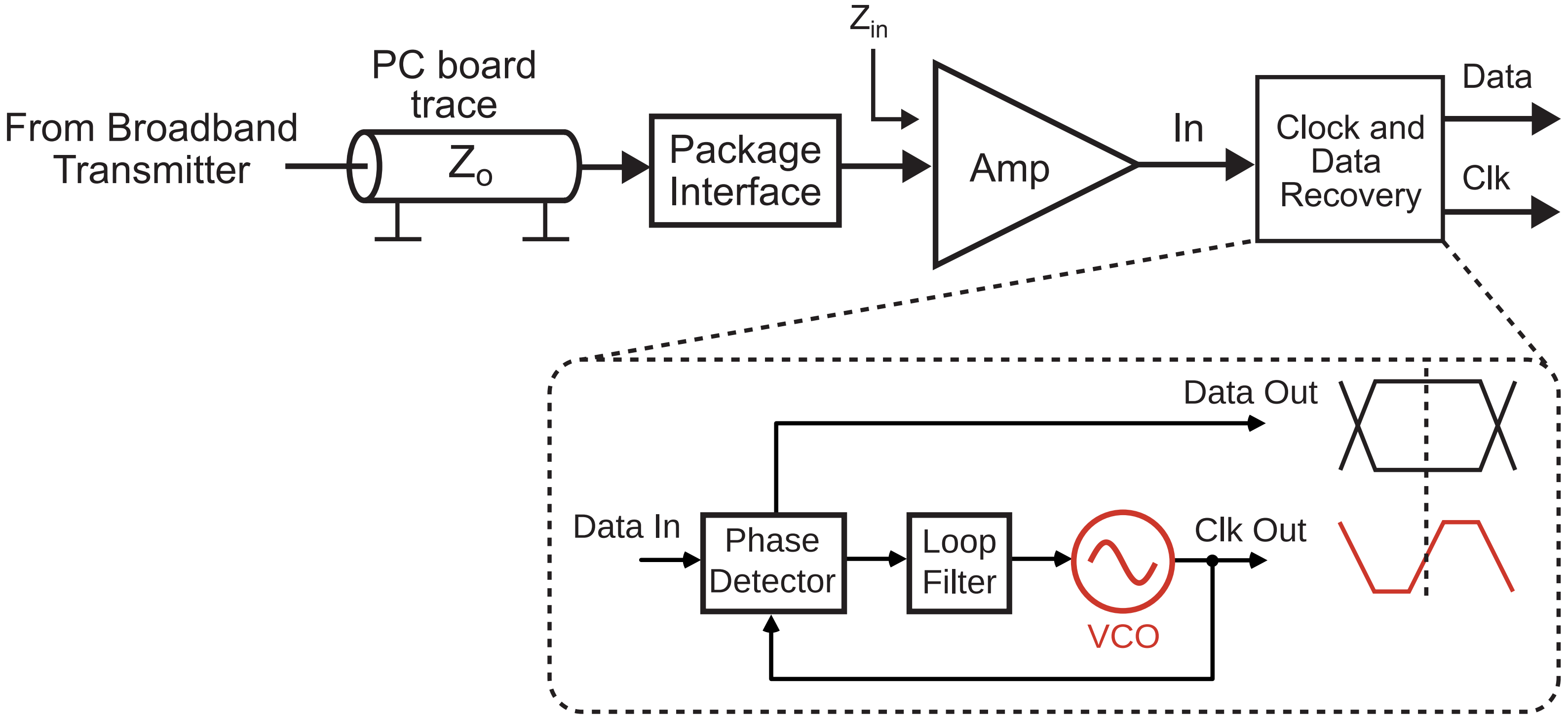
Michael Perrott
Massachusetts Institute of Technology

VCO Design for Wireless Systems



- **Design Issues**
  - **Tuning Range – need to cover all frequency channels**
  - **Noise – impacts receiver blocking and sensitivity performance**
  - **Power – want low power dissipation**
  - **Isolation – want to minimize noise pathways into VCO**
  - **Sensitivity to process/temp variations – need to make it manufacturable in high volume**

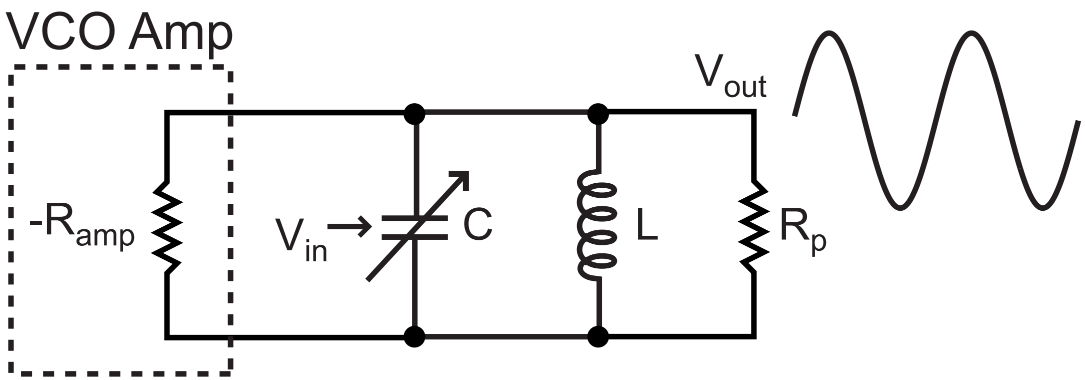
VCO Design For High Speed Data Links



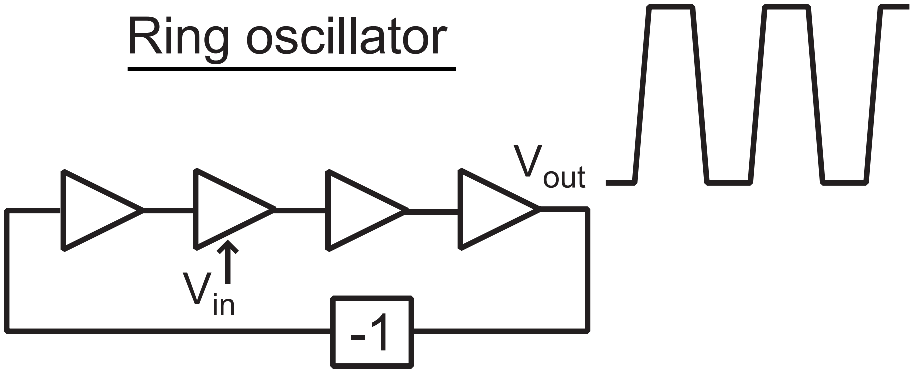
- **Design Issues**
  - **Same as wireless, but:**
    - Required noise performance is often less stringent
    - Tuning range is often narrower

Popular VCO Structures

LC oscillator

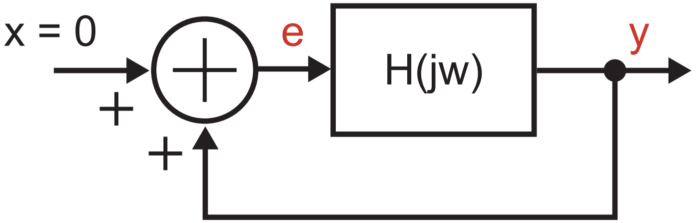


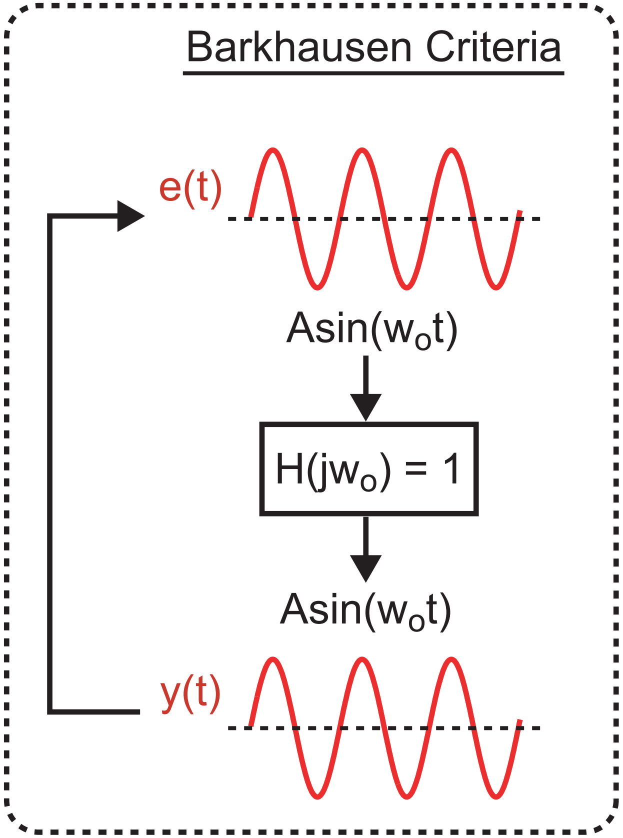
Ring oscillator



- **LC Oscillator: low phase noise, large area**
- **Ring Oscillator: easy to integrate, higher phase noise**

Barkhausen's Criteria for Oscillation





- **Closed loop transfer function**

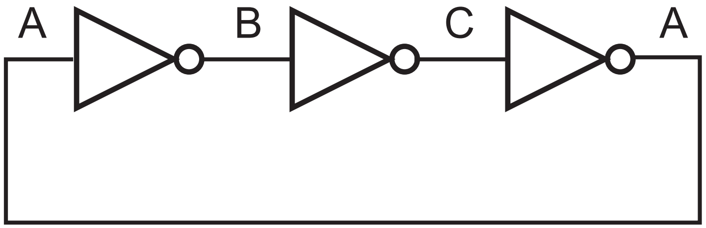
$$G(jw) = \frac{Y(jw)}{X(jw)} = \frac{H(jw)}{1 - H(jw)}$$

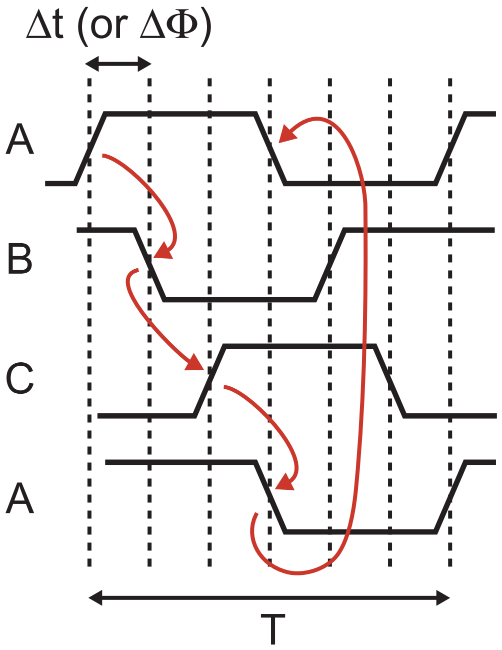
- **Self-sustaining oscillation at frequency w_o if**

$$H(jw_o) = 1$$

  - **Amounts to two conditions:**
    - Gain = 1 at frequency w_o
    - Phase = n360 degrees (n = 0,1,2,…) at frequency w_o

Example 1: Ring Oscillator





- **Gain is set to 1 by saturating characteristic of inverters**
- **Phase equals 360 degrees at frequency of oscillation**
  - **Assume N stages each with phase shift ΔΦ**

$$2N\Delta\Phi = 360^o \quad \Rightarrow \quad \Delta\Phi = \frac{180^o}{N}$$

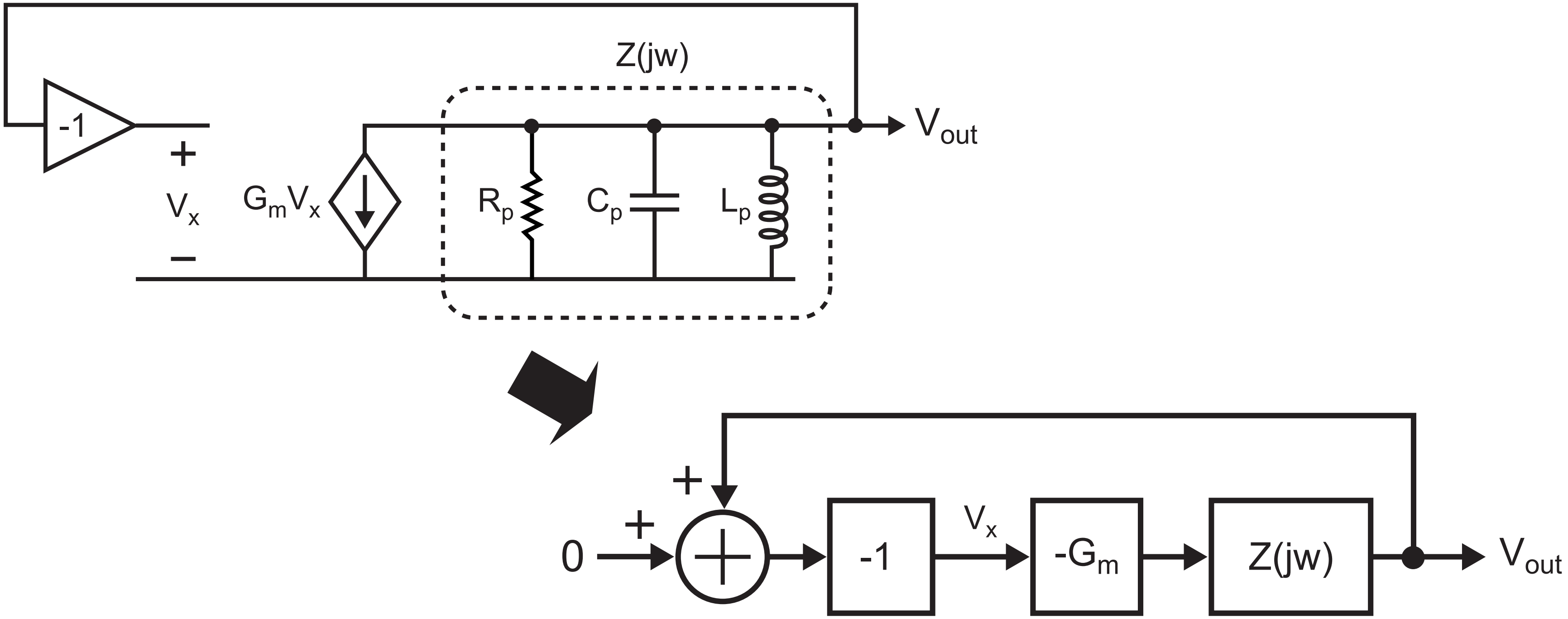
  - **Alternately, N stages with delay Δt**

$$2N\Delta t = T \quad \Rightarrow \quad \Delta t = \frac{T/2}{N}$$

Further Info on Ring Oscillators

- Due to their relatively poor phase noise performance, ring oscillators are rarely used in RF systems
  - They are used quite often in high speed data links, though
- We will focus on LC oscillators in this lecture
- Some useful info on CMOS ring oscillators
  - Maneatis et. al., “Precise Delay Generation Using Coupled Oscillators”, JSSC, Dec 1993 (look at pp 127-128 for delay cell description)
  - Todd Weigandt’s PhD thesis – http://kabuki.eecs.berkeley.edu/~weigandt/

Example 2: Resonator-Based Oscillator

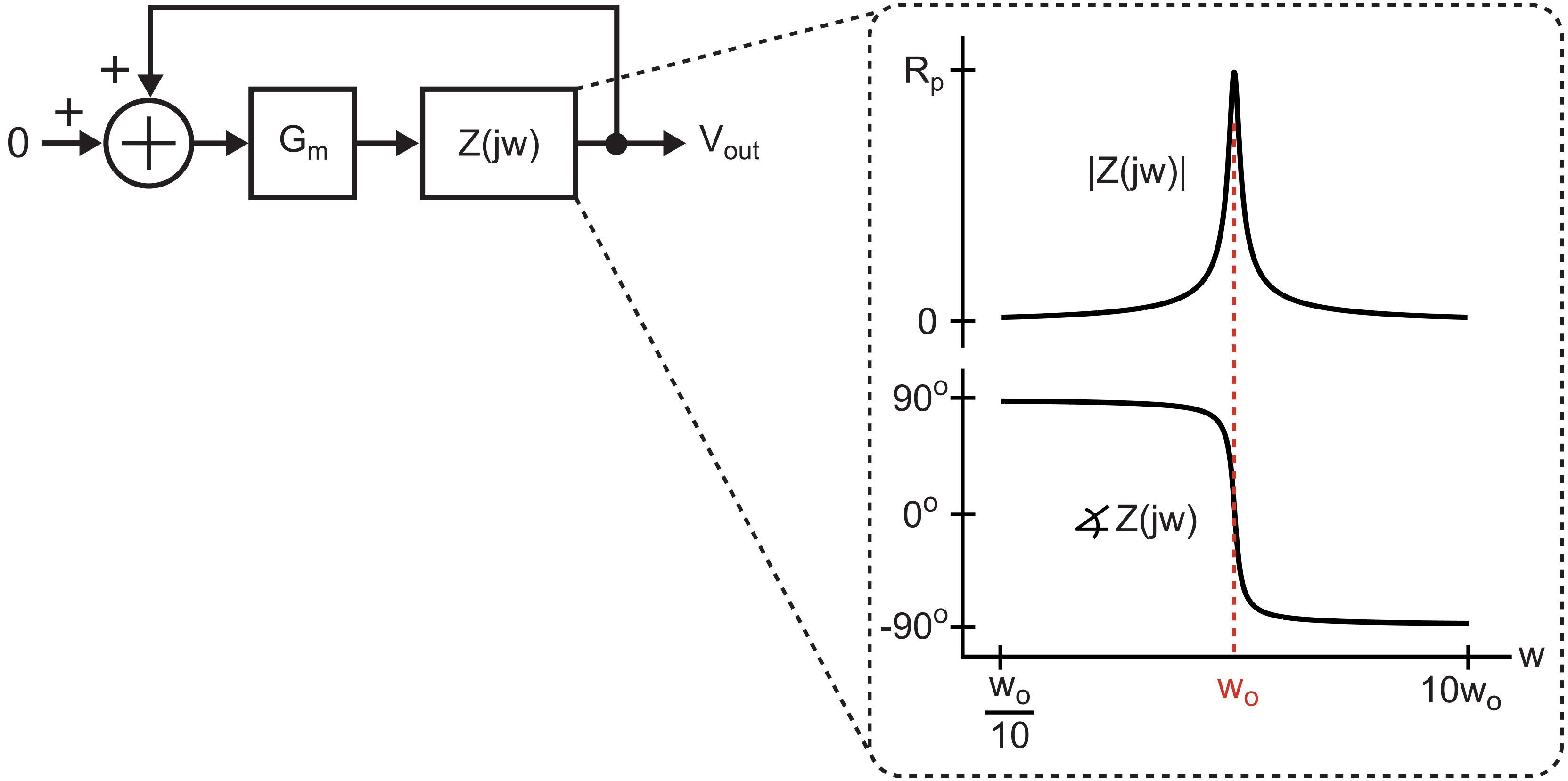


- **Barkhausen Criteria for oscillation at frequency w$_o$:**

$$G_m Z(jw_o) = 1$$

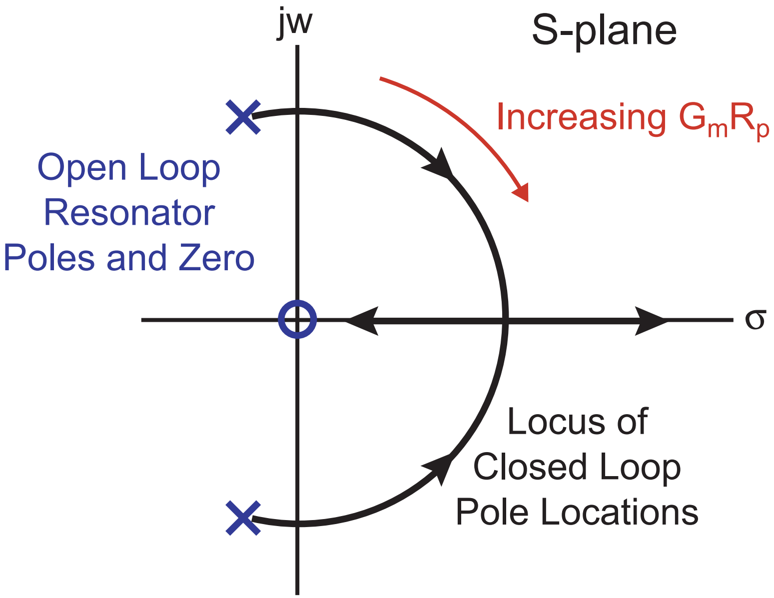
  - **Assuming G$_m$ is purely real, Z(jw$_o$) must also be purely real**

A Closer Look At Resonator-Based Oscillator



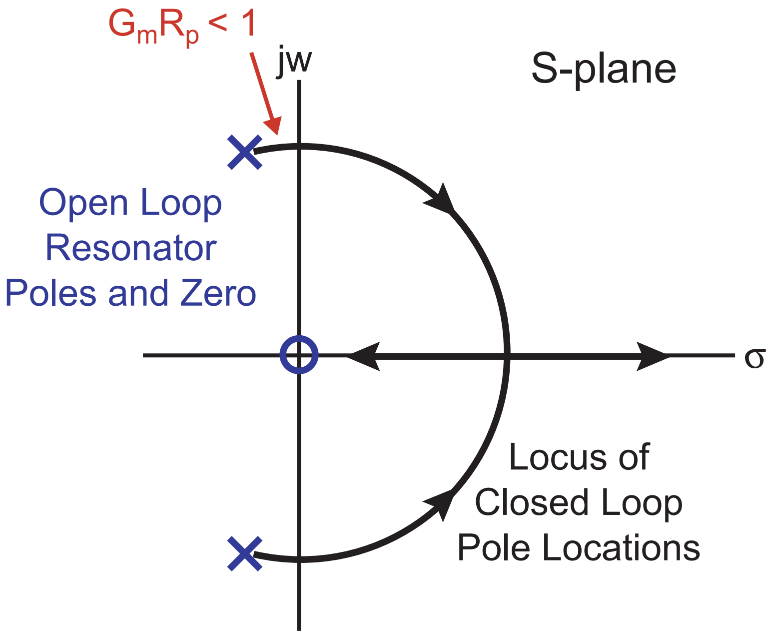
- **For parallel resonator at resonance**
  - **Looks like resistor (i.e., purely real) at resonance**
    - Phase condition is satisfied
    - Magnitude condition achieved by setting $G_mR_p = 1$

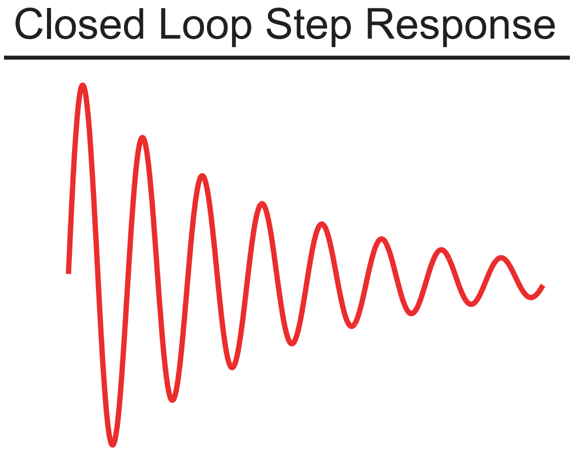
Impact of Different G_m Values



- **Root locus plot allows us to view closed loop pole locations as a function of open loop poles/zero and open loop gain (G_mR_p)**
  - **As gain (G_mR_p) increases, closed loop poles move into right half S-plane**

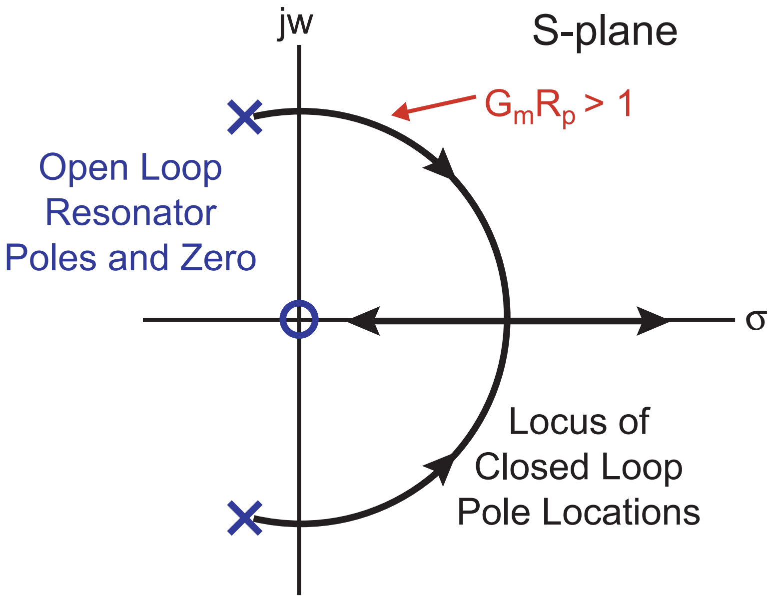
Impact of Setting G_m too low

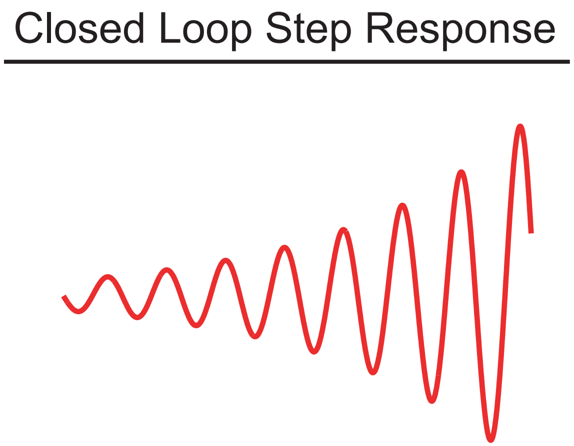




- **Closed loop poles end up in the left half S-plane**
  - **Underdamped response occurs**
    - Oscillation dies out

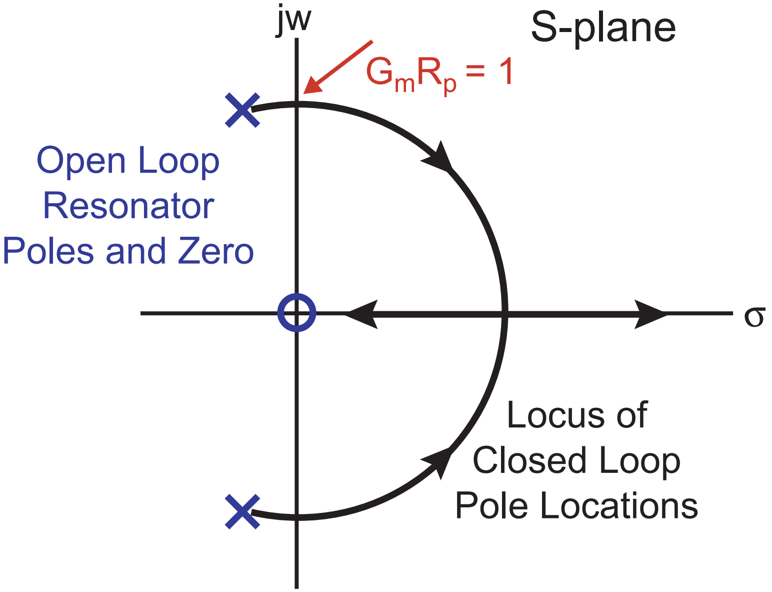
Impact of Setting G_m too High



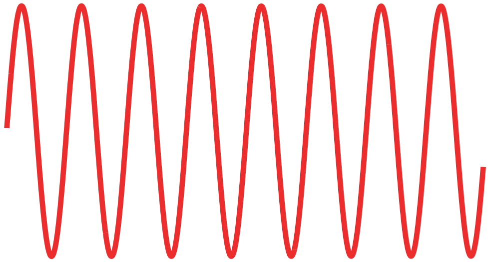


- **Closed loop poles end up in the right half S-plane**
  - **Unstable response occurs**
    - Waveform blows up!

Setting G_m To Just the Right Value

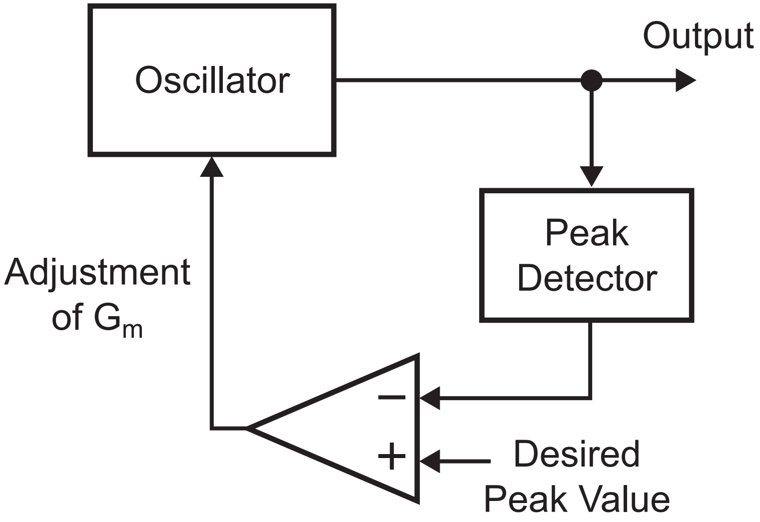


Closed Loop Step Response



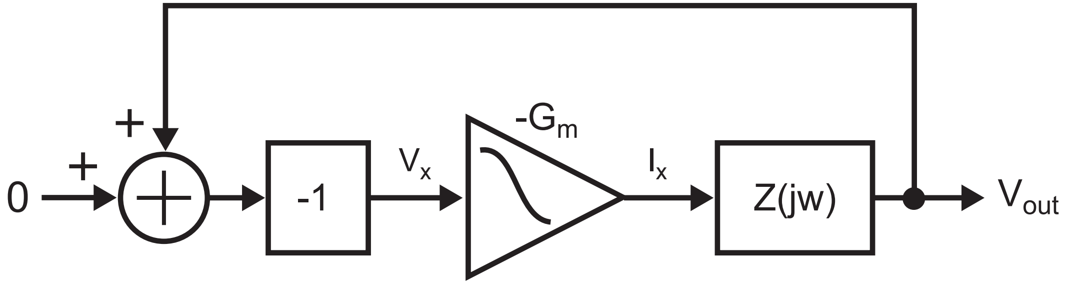
- **Closed loop poles end up on jw axis**
  - **Oscillation maintained**
- **Issue – G_mR_p needs to *exactly* equal 1**
  - **How do we achieve this in practice?**

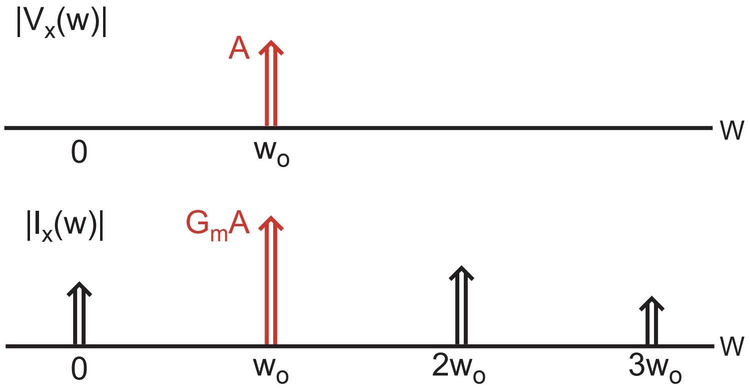
Amplitude Feedback Loop



- **One thought is to detect oscillator amplitude, and then adjust G_m so that it equals a desired value**
  - **By using feedback, we can precisely achieve $G_mR_p = 1$**
- **Issues**
  - **Complex, requires power, and adds noise**

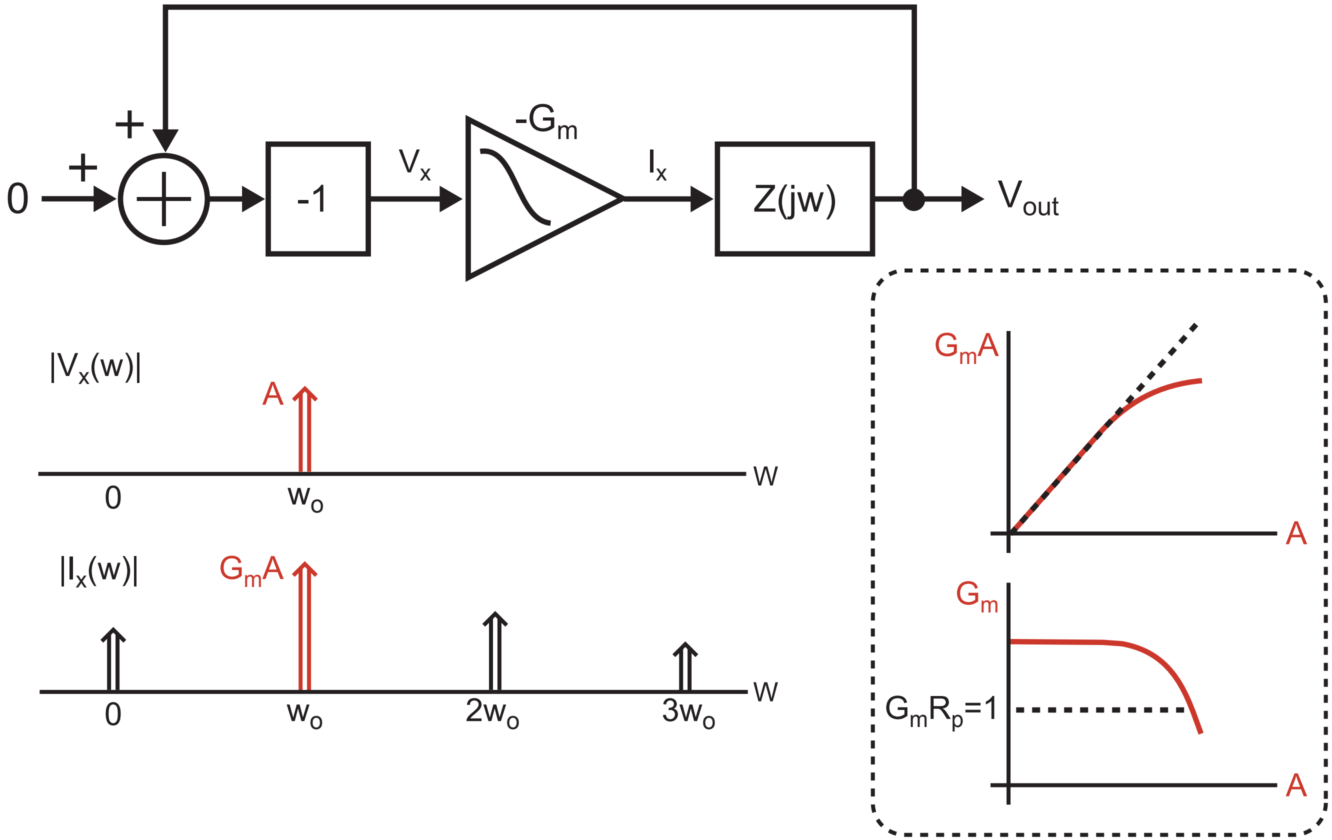
Leveraging Amplifier Nonlinearity as Feedback





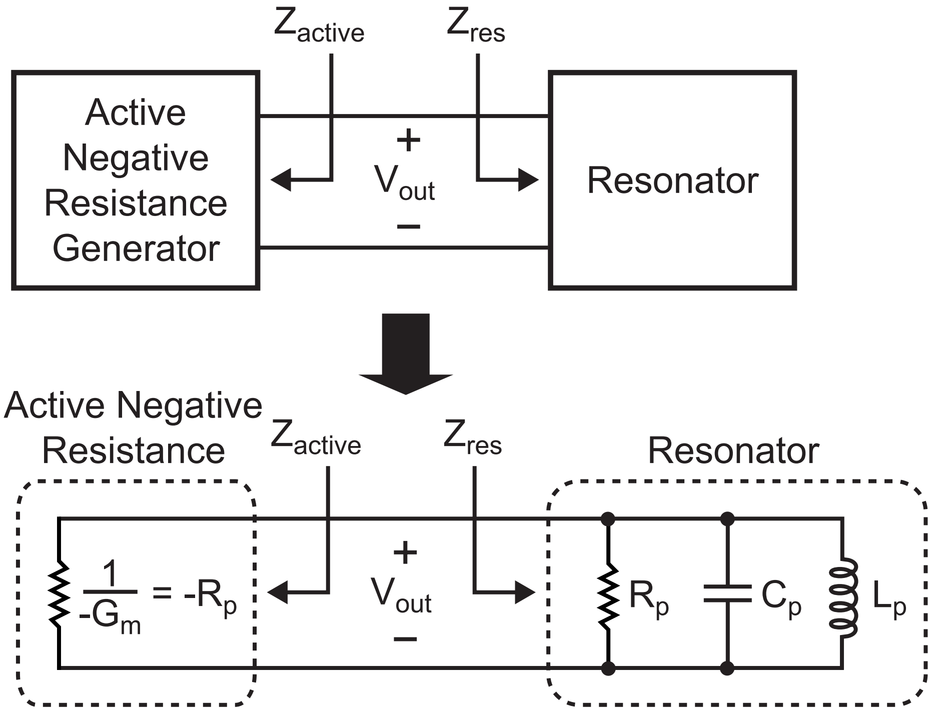
- **Practical transconductance amplifiers have saturating characteristics**
  - **Harmonics created, but filtered out by resonator**
  - **Our interest is in the relationship between the input and the fundamental of the output**

Leveraging Amplifier Nonlinearity as Feedback



- **As input amplitude is increased**
  - **Effective gain from input to fundamental of output drops**
  - **Amplitude feedback occurs! (G_mR_p = 1 in steady-state)**

One-Port View of Resonator-Based Oscillators

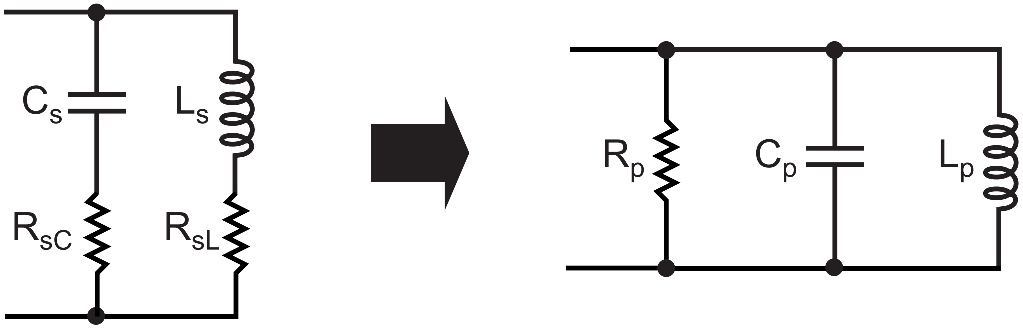


- **Convenient for intuitive analysis**
- **Here we seek to cancel out loss in tank with a negative resistance element**
  - **To achieve sustained oscillation, we must have**

$$\frac{1}{G_m} = R_p \quad \Rightarrow \quad G_m R_p = 1$$

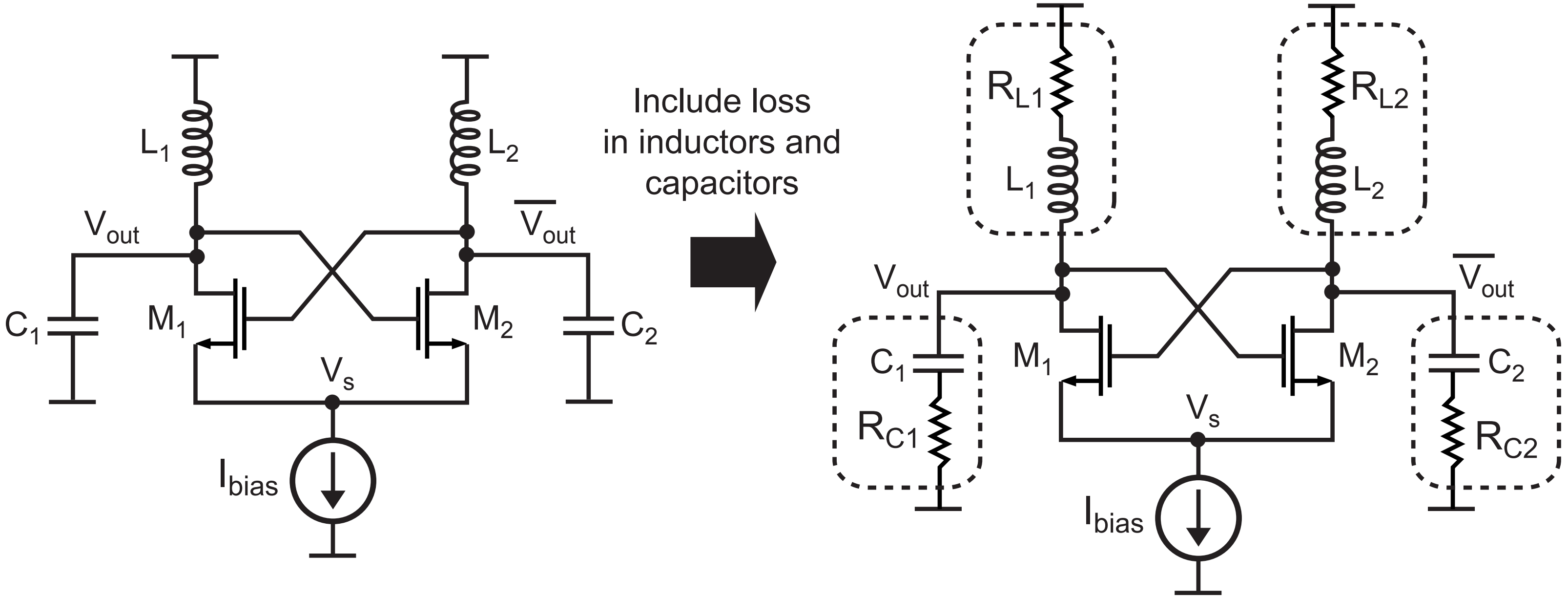
One-Port Modeling Requires Parallel RLC Network

- **Since VCO operates over a very narrow band of frequencies, we can always do series to parallel transformations to achieve a parallel network for analysis**



  - **Warning – in practice, RLC networks can have secondary (or more) resonant frequencies, which cause undesirable behavior**
    - Equivalent parallel network masks this problem in hand analysis
    - Simulation will reveal the problem

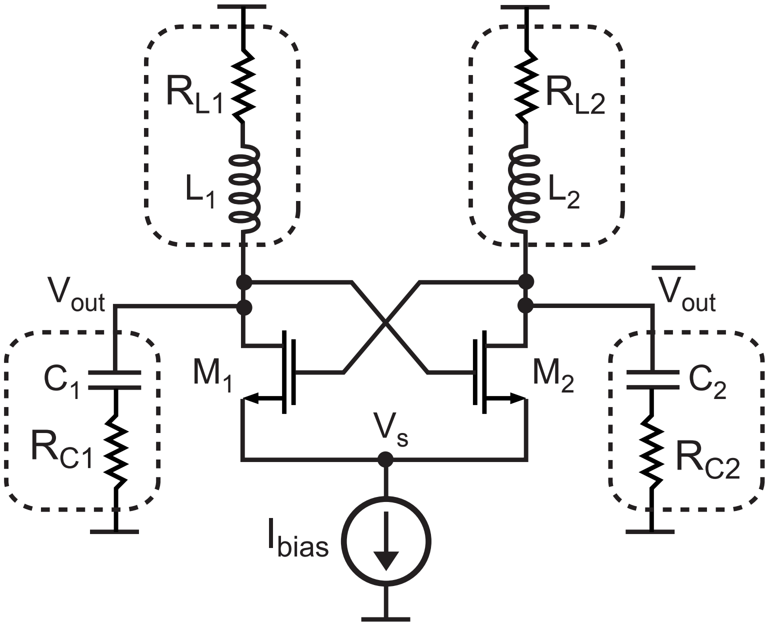
Example – Negative Resistance Oscillator



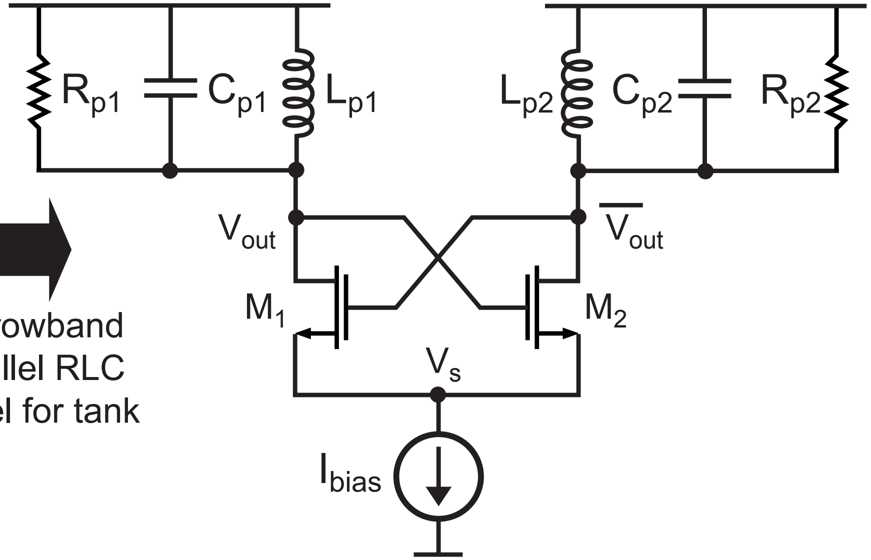
Include loss in inductors and capacitors

- **This type of oscillator structure is quite popular in current CMOS implementations**
  - **Advantages**
    - Simple topology
    - Differential implementation (good for feeding differential circuits)
    - Good phase noise performance can be achieved

Analysis of Negative Resistance Oscillator (Step 1)

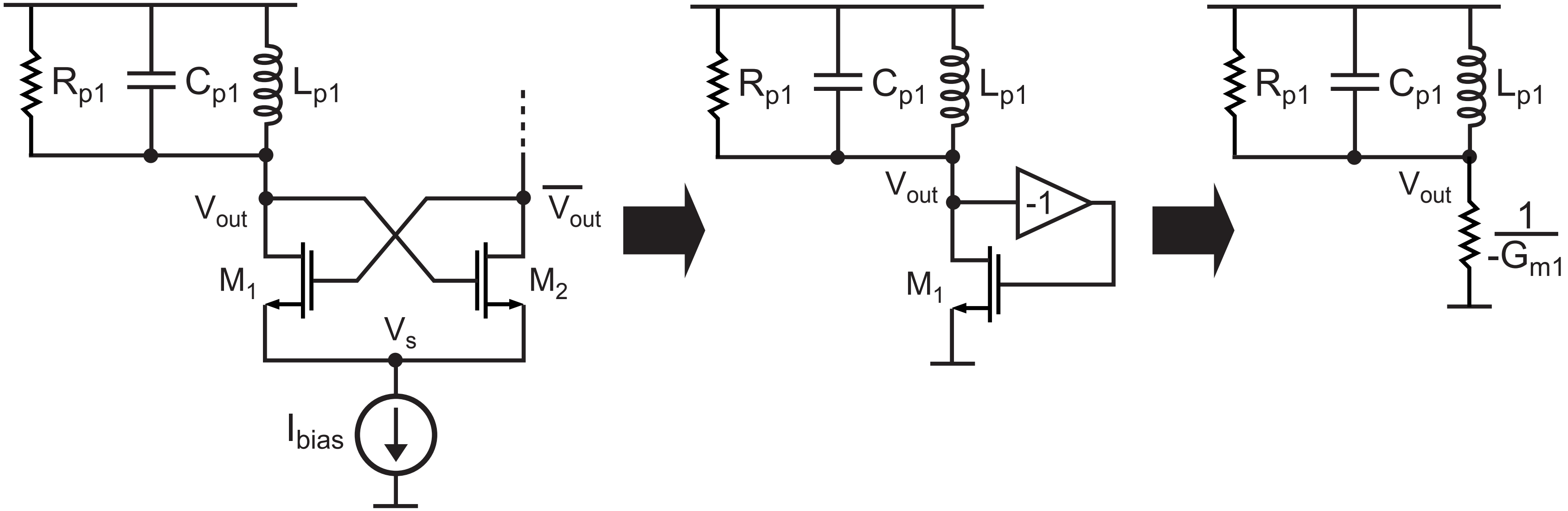


Narrowband parallel RLC model for tank



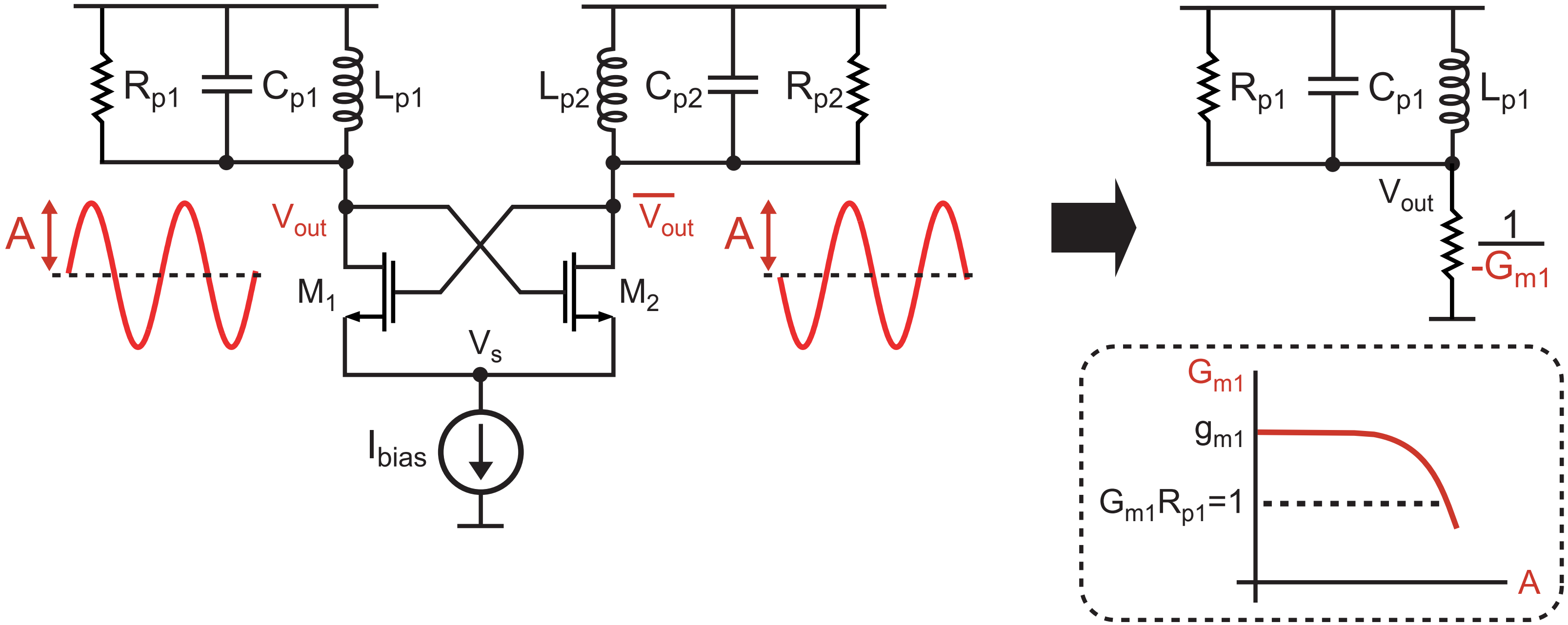
- **Derive a parallel RLC network that includes the loss of the tank inductor and capacitor**
  - **Typically, such loss is dominated by series resistance in the inductor**

Analysis of Negative Resistance Oscillator (Step 2)



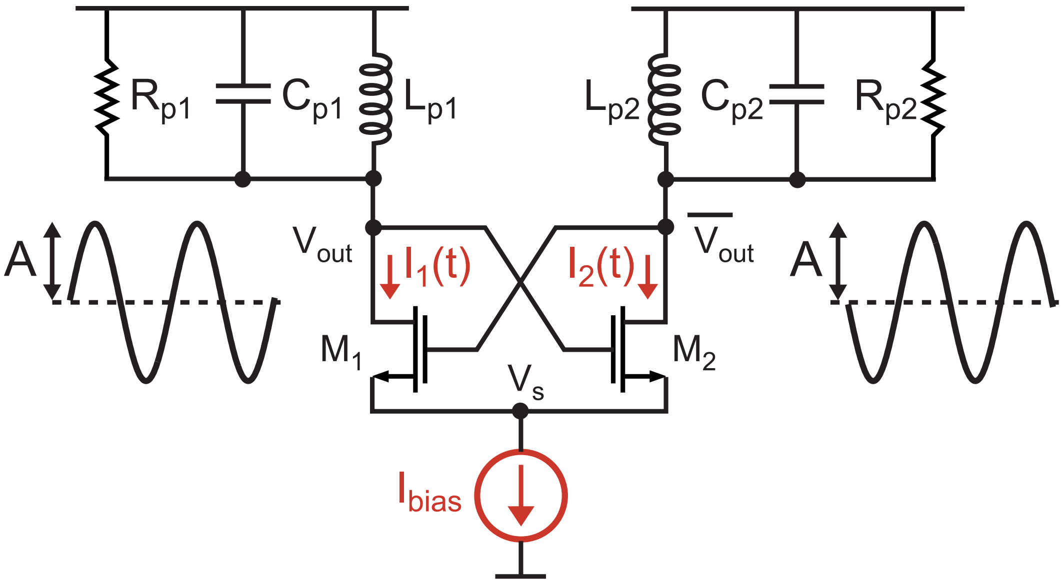
- **Split oscillator circuit into half circuits to simplify analysis**
  - **Leverages the fact that we can approximate V_s as being incremental ground (this is not quite true, but close enough)**
- **Recognize that we have a diode connected device with a negative transconductance value**
  - **Replace with negative resistor**
    - Note: G_m is ***large signal*** transconductance value

Design of Negative Resistance Oscillator



- **Design tank components to achieve high Q**
  - **Resulting R_p value is as large as possible**
- **Choose bias current (I_{bias}) for large swing (without going far into saturation)**
  - **We'll estimate swing as a function of I_{bias} shortly**
- **Choose transistor size to achieve adequately large g_{m1}**
  - **Usually twice as large as $1/R_{p1}$ to guarantee startup**

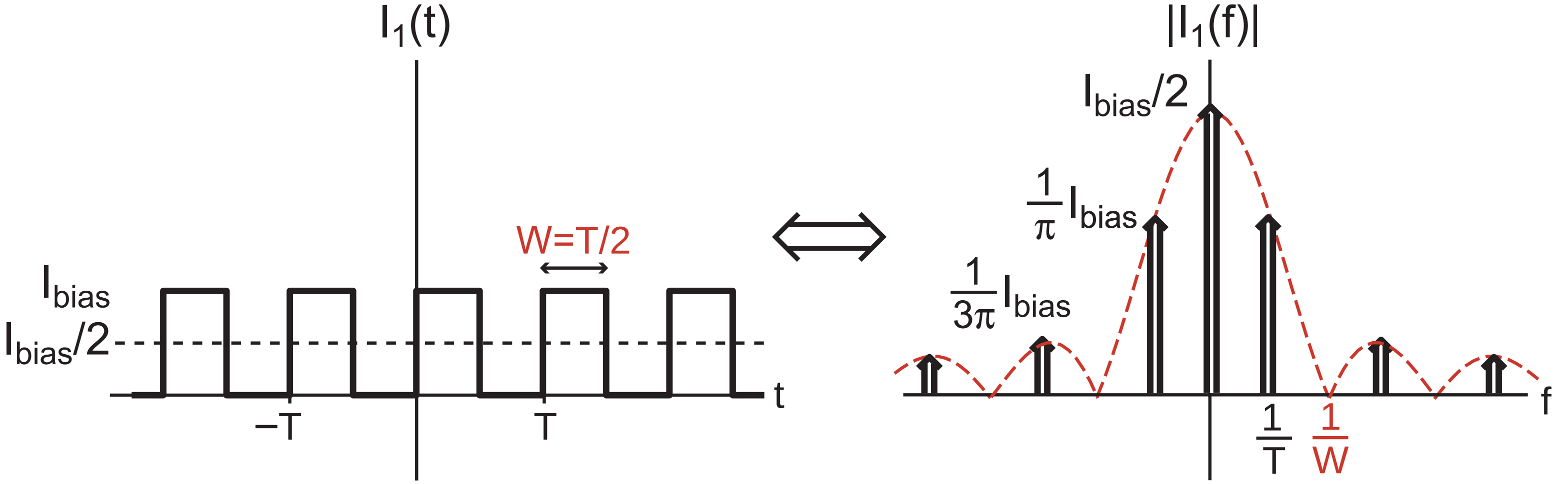
Calculation of Oscillator Swing



- **Design tank components to achieve high Q**
  - **Resulting R_p value is as large as possible**
- **Choose bias current (I_{bias}) for large swing (without going far into saturation)**
  - **We'll estimate swing as a function of I_{bias} in next slide**
- **Choose transistor size to achieve adequately large g_{m1}**
  - **Usually twice as large as $1/R_{p1}$ to guarantee startup**

Calculation of Oscillator Swing as a Function of I_{bias}

- **By symmetry, assume $I_1(t)$ is a square wave**
  - **We are interested in determining fundamental component**
    - (DC and harmonics filtered by tank)



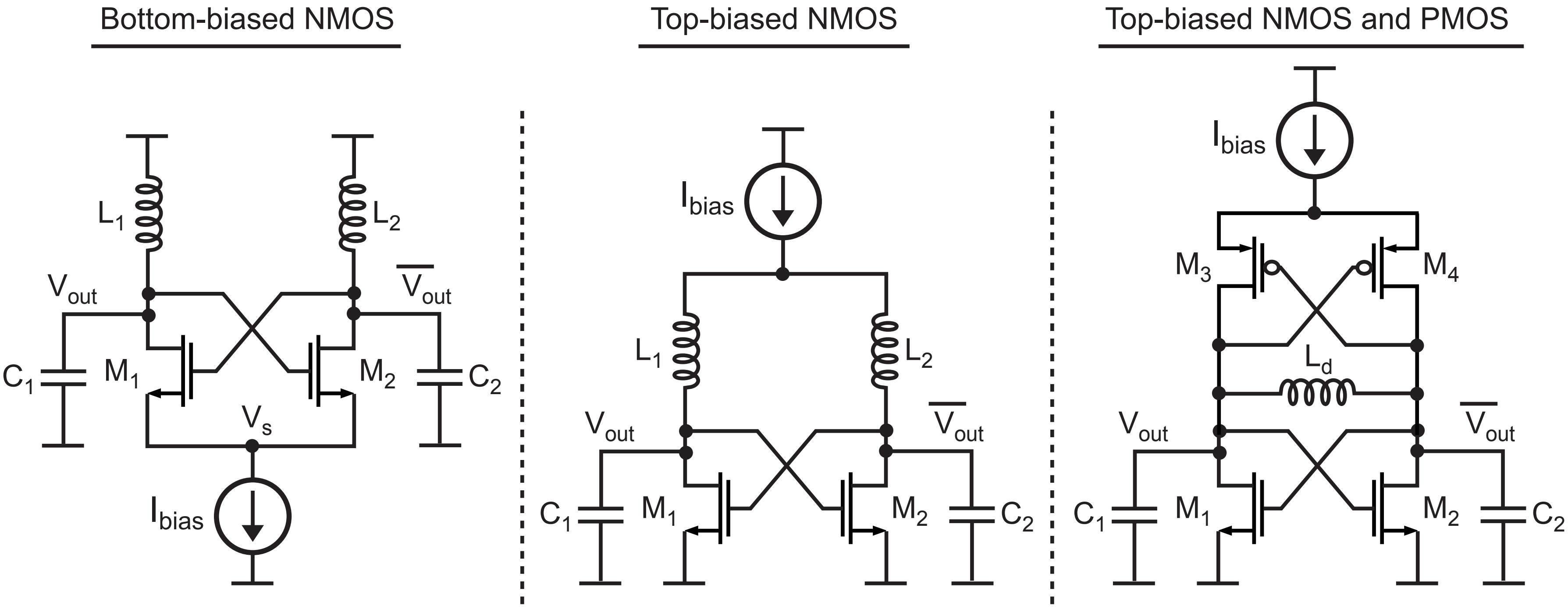
  - **Fundamental component is**

$$I_1(t)\Big|_{fundamental} = \frac{2}{\pi} I_{bias}\,\mathrm{sin}(w_o t), \quad \text{where} \;\; w_o = \frac{2\pi}{T}$$

  - **Resulting oscillator amplitude**

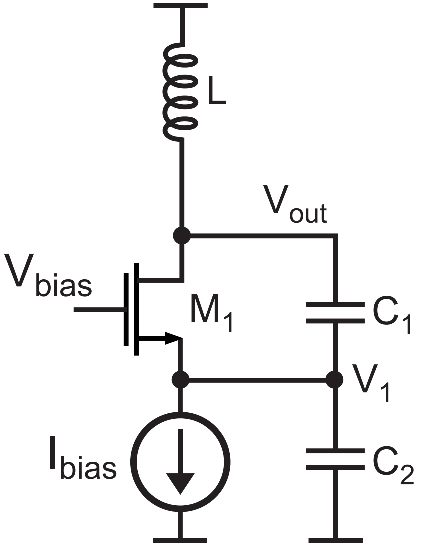
$$\boxed{A = \frac{2}{\pi} I_{bias} R_p}$$

Variations on a Theme



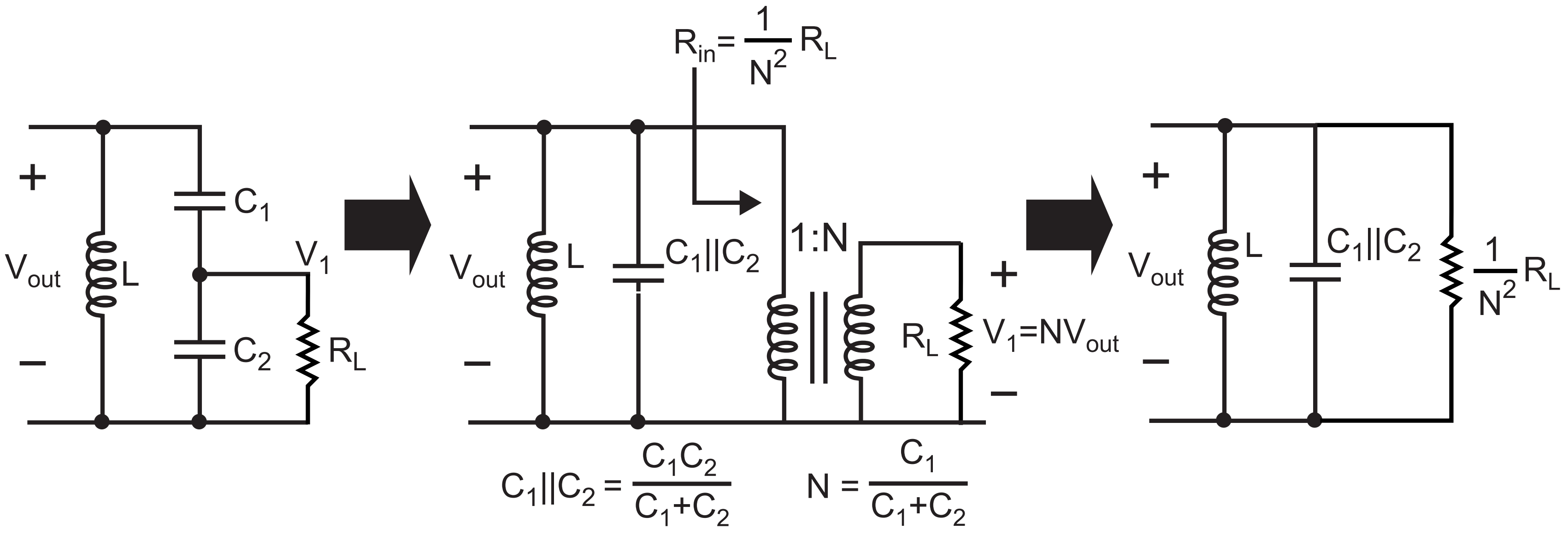
- Biasing can come from top or bottom
- Can use either NMOS, PMOS, or both for transconductor
  - Use of both NMOS and PMOS for coupled pair would appear to achieve better phase noise at a given power dissipation
    - See Hajimiri et. al, “Design Issues in CMOS Differential LC Oscillators”, JSSC, May 1999 and Feb, 2000 (pp 286-287)

Colpitts Oscillator



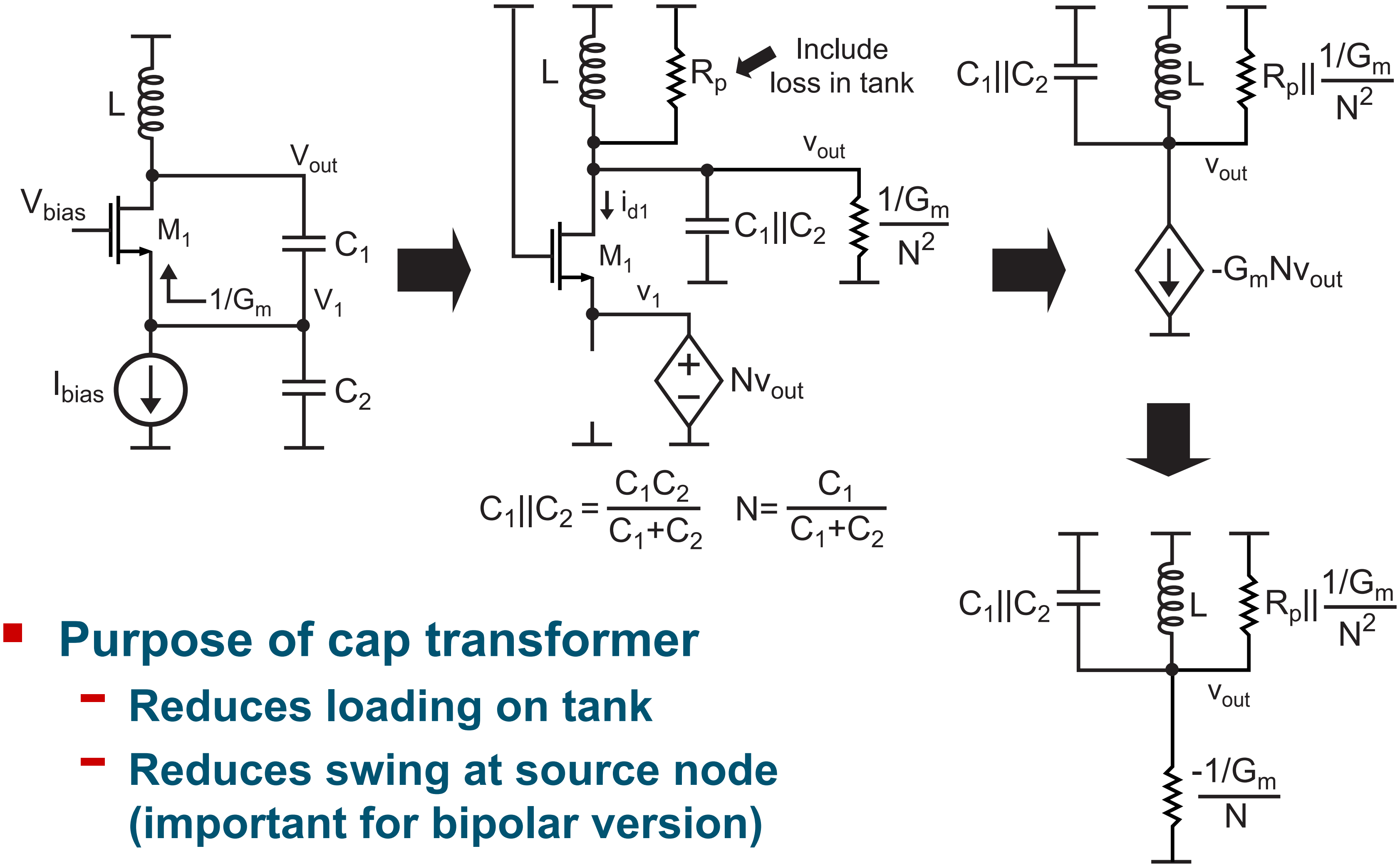
- Carryover from discrete designs in which single-ended approaches were preferred for simplicity
  - Achieves negative resistance with only one transistor
  - Differential structure can also be implemented
- Good phase noise can be achieved, but not apparent there is an advantage of this design over negative resistance design for CMOS applications

Analysis of Cap Transformer used in Colpitts



- **Voltage drop across R_L is reduced by capacitive voltage divider**
  - **Assume that impedances of caps are less than R_L at resonant frequency of tank (simplifies analysis)**
    - Ratio of V_1 to V_{out} set by caps and not R_L
- **Power conservation leads to transformer relationship shown**

Simplified Model of Colpitts

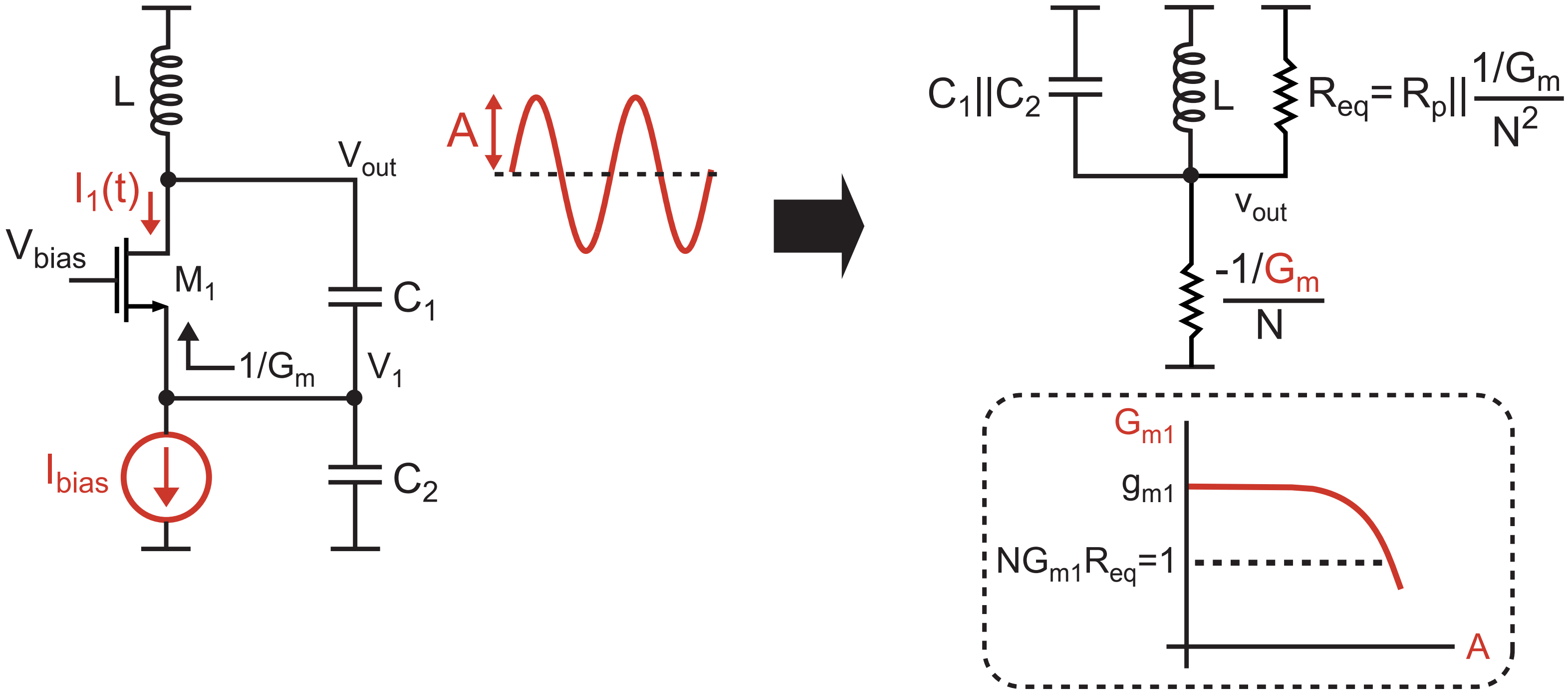


Include loss in tank

$$C_1||C_2 = \frac{C_1C_2}{C_1+C_2} \qquad N = \frac{C_1}{C_1+C_2}$$

- **Purpose of cap transformer**
  - **Reduces loading on tank**
  - **Reduces swing at source node (important for bipolar version)**
- **Transformer ratio set to achieve best noise performance**

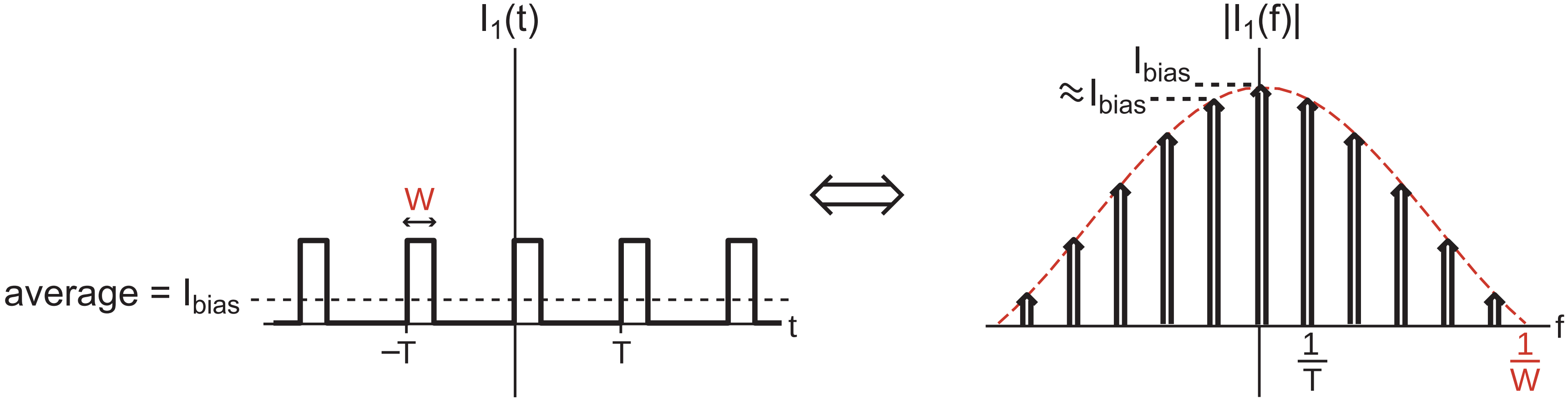
Design of Colpitts Oscillator



- **Design tank for high Q**
- **Choose bias current (I_{bias}) for large swing (without going far into saturation)**
- **Choose transformer ratio for best noise**
  - **Rule of thumb: choose N = 1/5 according to Tom Lee**
- **Choose transistor size to achieve adequately large g_{m1}**

Calculation of Oscillator Swing as a Function of I_{bias}

- $I_1(t)$ consists of pulses whose shape and width are a function of the transistor behavior and transformer ratio
  - Approximate as narrow square wave pulses with width W



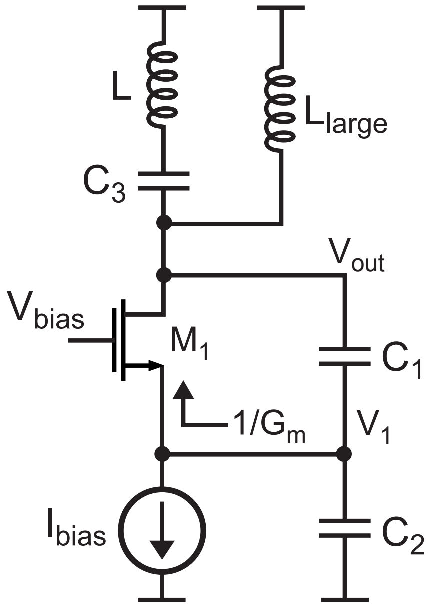
  - Fundamental component is

$$I_1(t)\Big|_{fundamental} \approx 2I_{bias}\sin(w_o t), \quad \text{where} \quad w_o = \frac{2\pi}{T}$$

  - Resulting oscillator amplitude

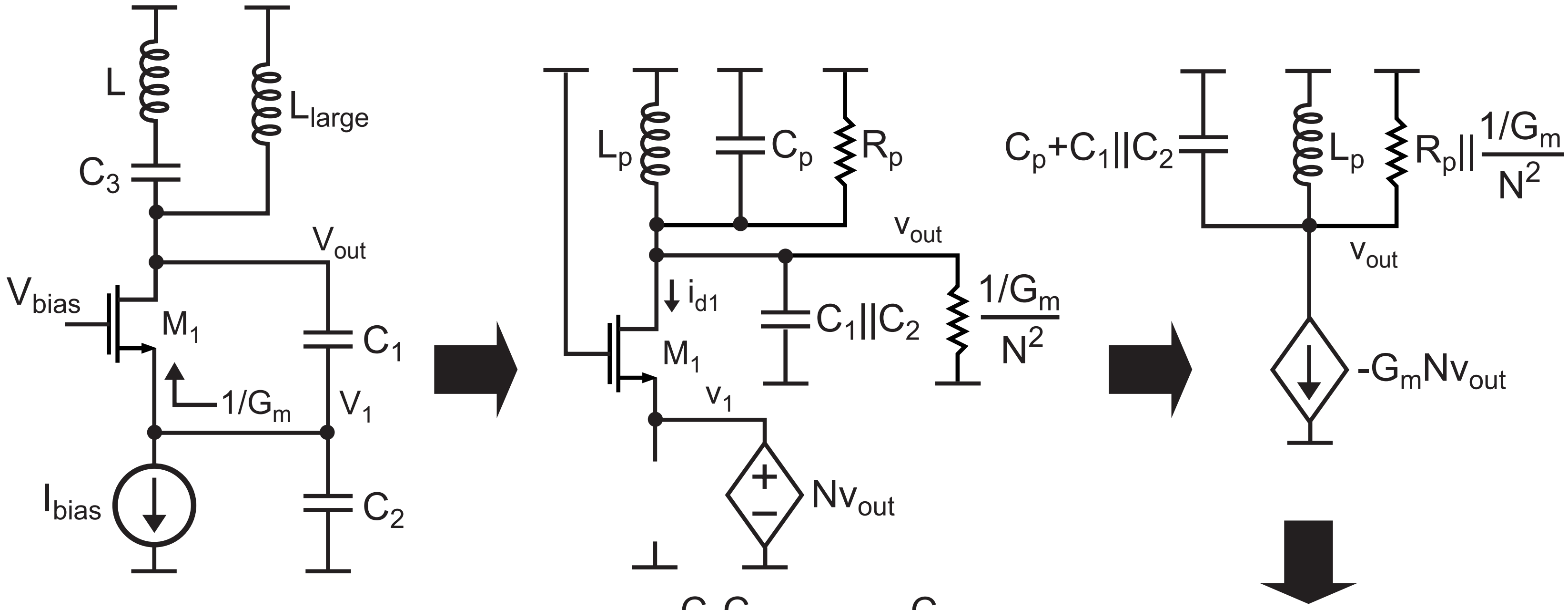
$$\boxed{A \approx 2I_{bias}R_{eq}}$$

Clapp Oscillator

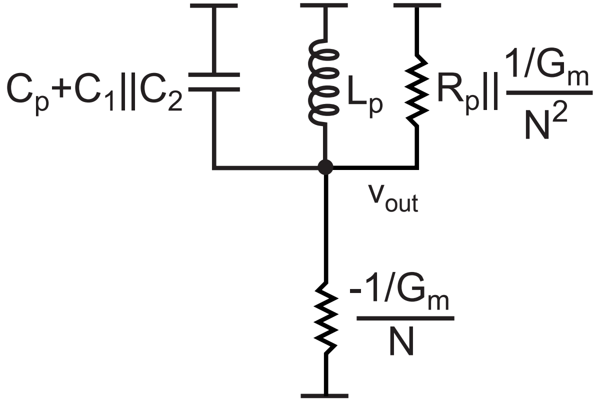


- **Same as Colpitts except that inductor portion of tank is isolated from the drain of the device**
  - **Allows inductor voltage to achieve a larger amplitude without exceeded the max allowable voltage at the drain**
    - Good for achieving lower phase noise

Simplified Model of Clapp Oscillator

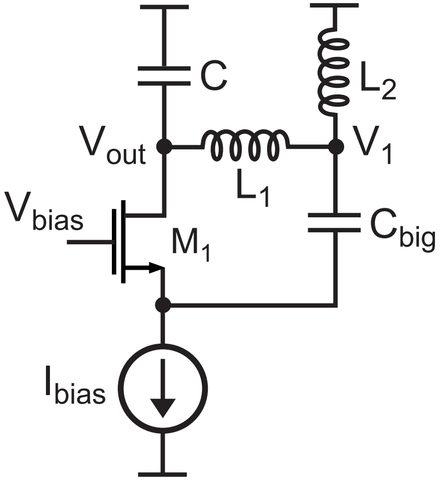


$$C_1||C_2 = \frac{C_1C_2}{C_1+C_2} \qquad N = \frac{C_1}{C_1+C_2}$$



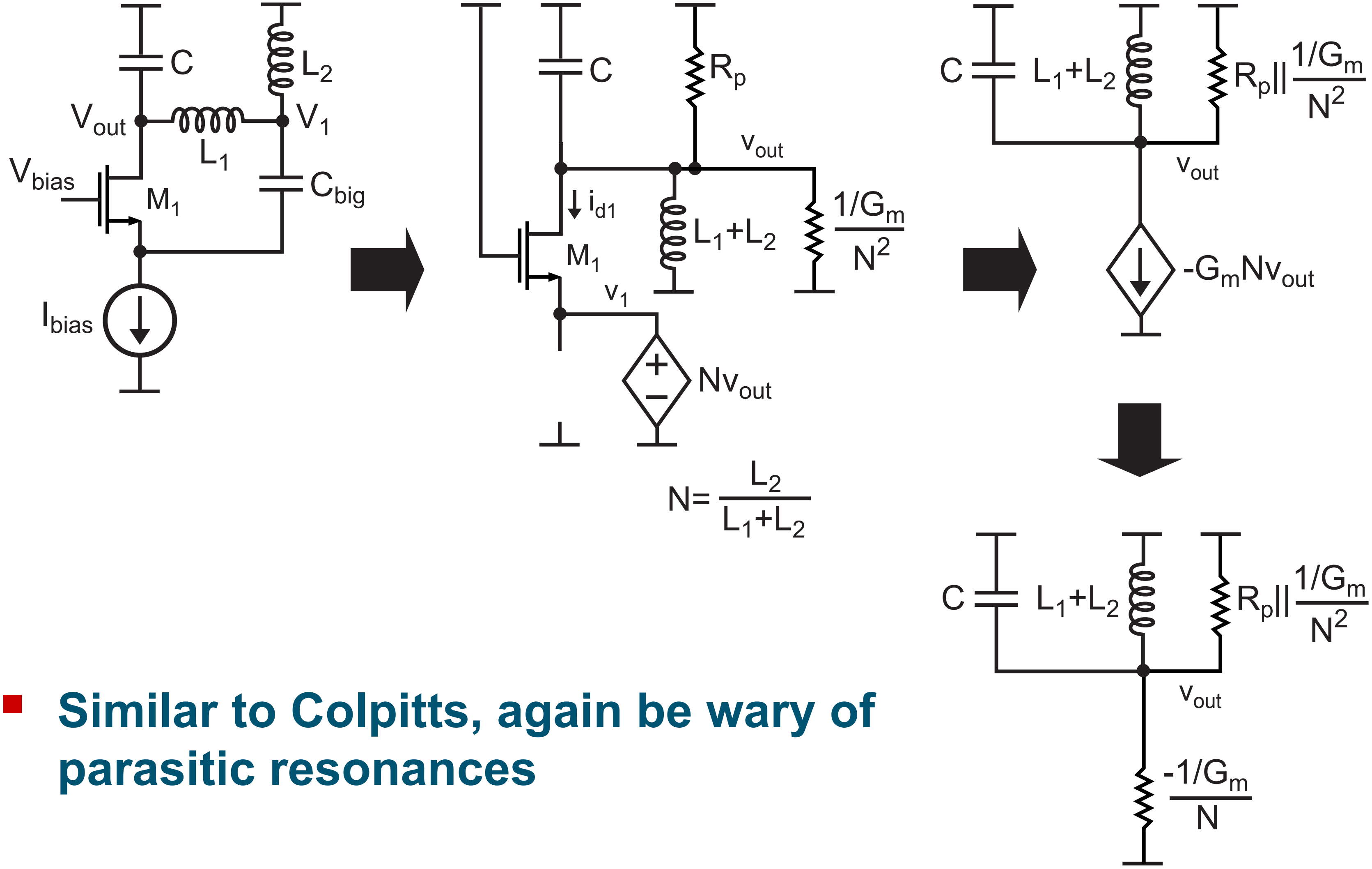
- **Looks similar to Colpitts model**
  - **Be careful of parasitic resonances!**

Hartley Oscillator



- **Same as Colpitts, but uses a tapped inductor rather than series capacitors to implement the transformer portion of the circuit**
  - **Not popular for IC implementations due to the fact that capacitors are easier to realize than inductors**

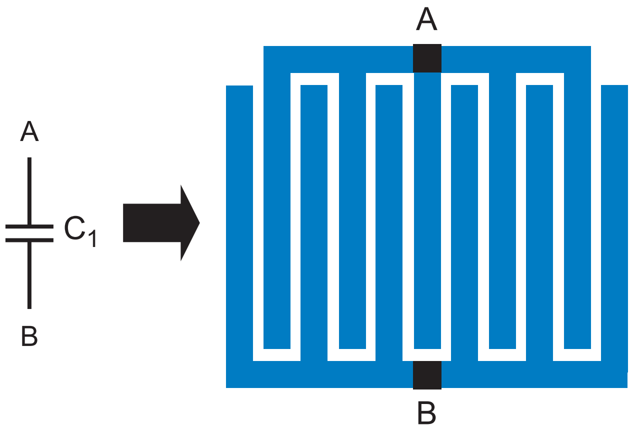
Simplified Model of Hartley Oscillator

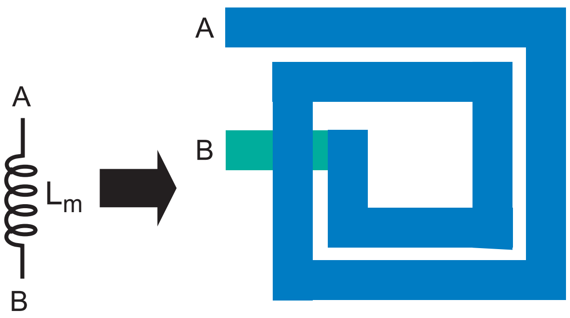


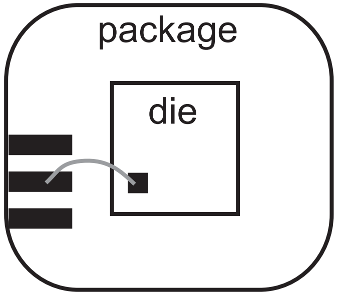
- **Similar to Colpitts, again be wary of parasitic resonances**

Integrated Resonator Structures

- Inductor and capacitor tank
  - Lateral caps have high Q (> 50)
  - Spiral inductors have moderate Q (5 to 10), but completely integrated and have tight tolerance (< ± 10%)
  - Bondwire inductors have high Q (> 40), but not as “integrated” and have poor tolerance (> ± 20%)
  - Note: see Lecture 4 for more info on these

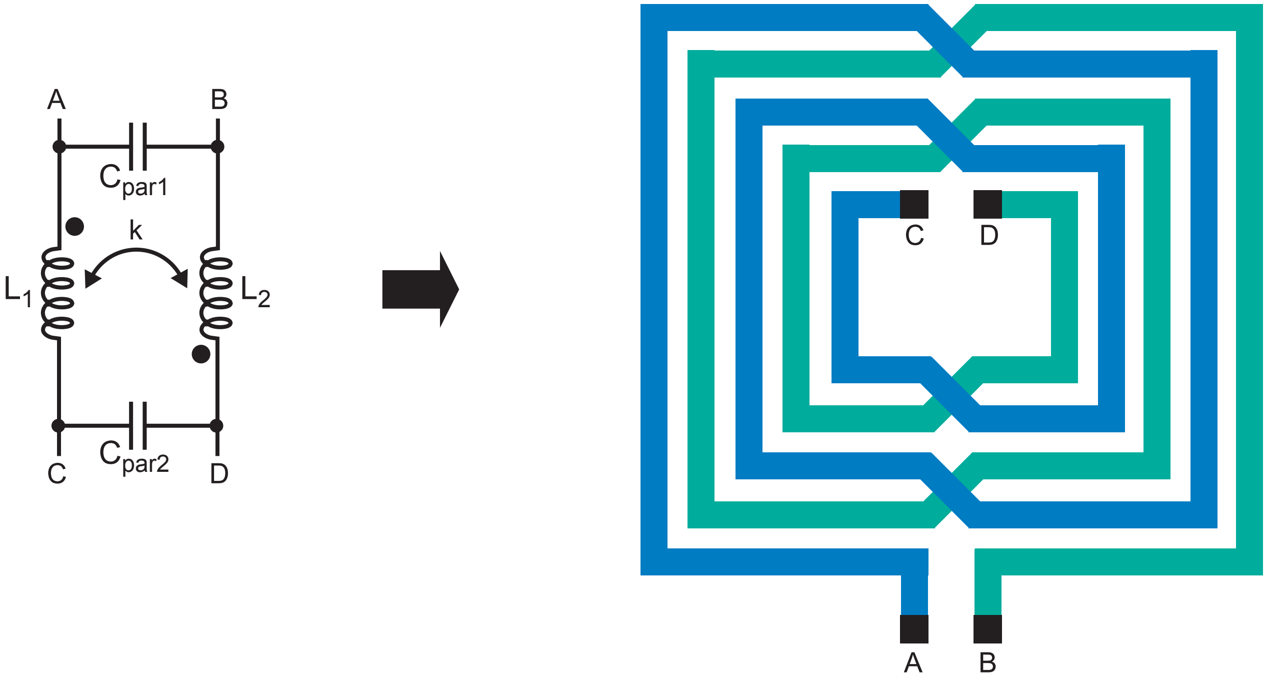

Lateral Capacitor


Spiral Inductor

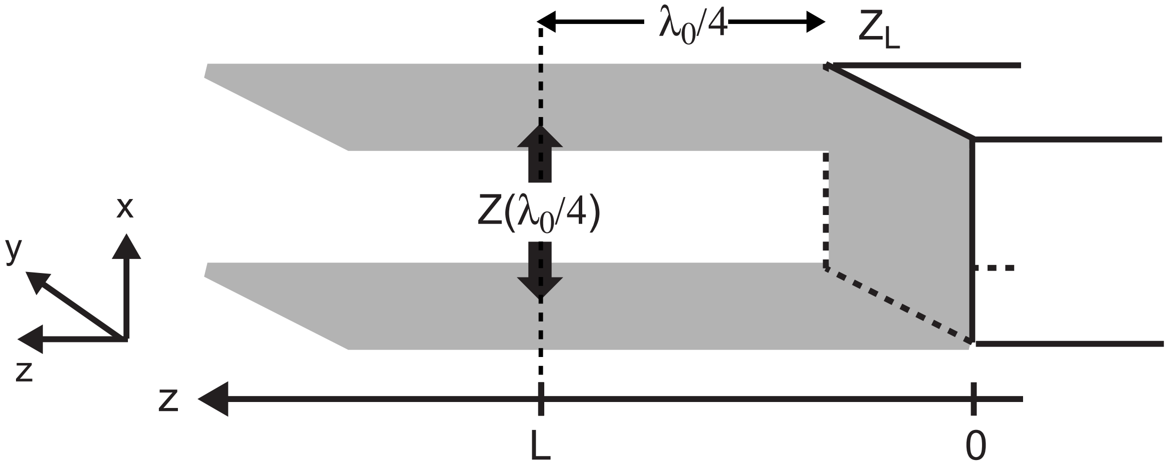

Bondwire Inductor

Integrated Resonator Structures

- **Integrated transformer**
  - **Leverages self and mutual inductance for resonance to achieve higher Q**
  - **See Straayer et. al., “A low-noise transformer-based 1.7 GHz CMOS VCO”, ISSCC 2002, pp 286-287**



Quarter Wave Resonator



- Impedance calculation (from Lecture 4)

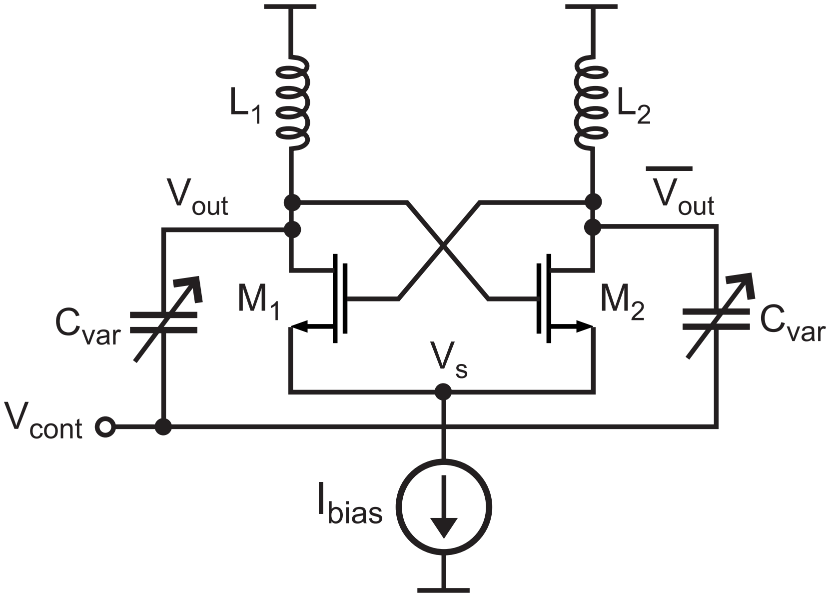
$$Z(\lambda_o/4) \approx -j\frac{2}{\pi}\sqrt{\frac{L}{C}}\left(\frac{w_o}{\Delta w}\right)$$

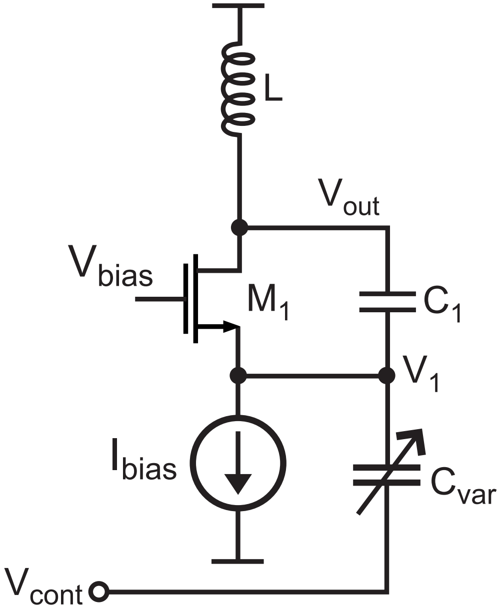
  - Looks like parallel LC tank!
- Benefit – very high Q can be achieved with fancy dielectric
- Negative – relatively large area (external implementation in the past), but getting smaller with higher frequencies!

Other Types of Resonators

- Quartz crystal
  - Very high Q, and very accurate and stable resonant frequency
    - Confined to low frequencies (< 200 MHz)
    - Non-integrated
  - Used to create low noise, accurate, “reference” oscillators
- SAW devices
  - High frequency, but poor accuracy (for resonant frequency)
- MEMS devices
  - Cantilever beams – promise high Q, but non-tunable and haven’t made it to the GHz range, yet, for resonant frequency
  - FBAR – Q > 1000, but non-tunable and poor accuracy
  - Other devices are on the way!

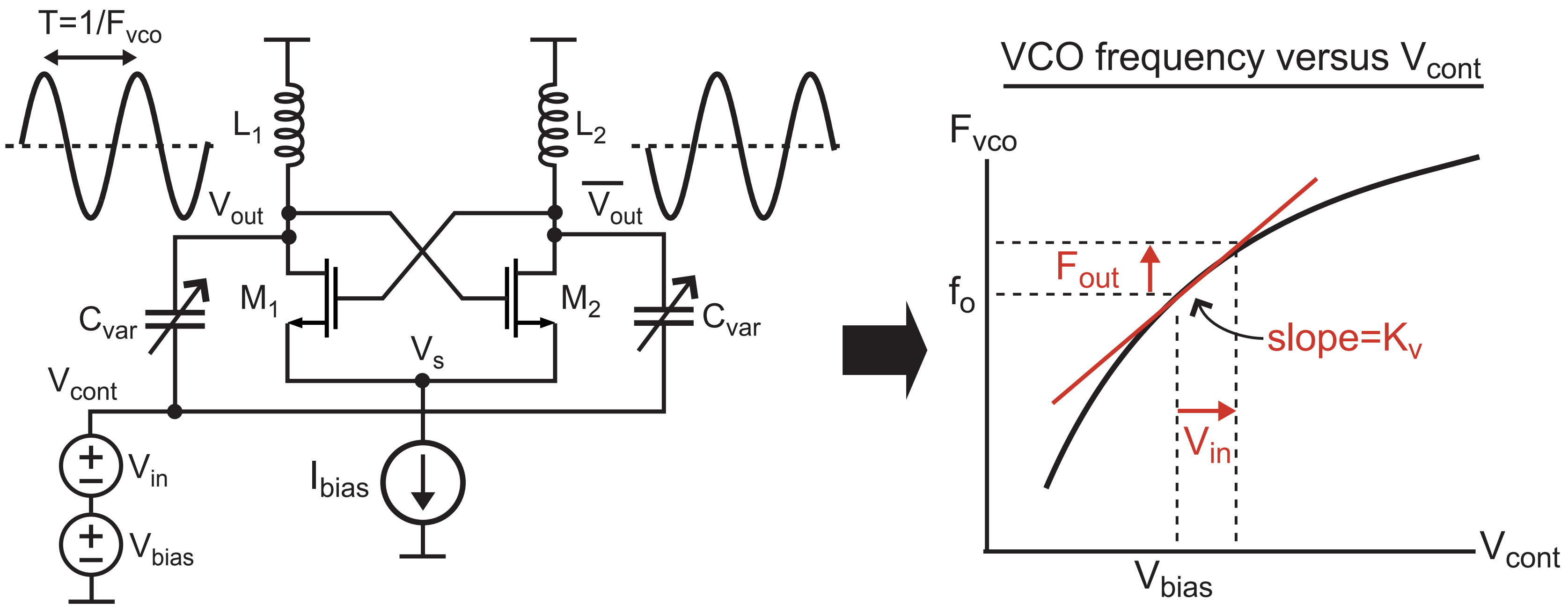
Voltage Controlled Oscillators (VCO's)





- **Include a tuning element to adjust oscillation frequency**
  - **Typically use a variable capacitor (varactor)**
- **Varactor incorporated by replacing fixed capacitance**
  - **Note that much fixed capacitance cannot be removed (transistor junctions, interconnect, etc.)**
    - Fixed cap lowers frequency tuning range

Model for Voltage to Frequency Mapping of VCO



- **Model VCO in a small signal manner by looking at deviations in frequency about the bias point**
  - **Assume linear relationship between input voltage and output frequency**

$$\boxed{F_{out}(t) = K_v v_{in}(t)}$$

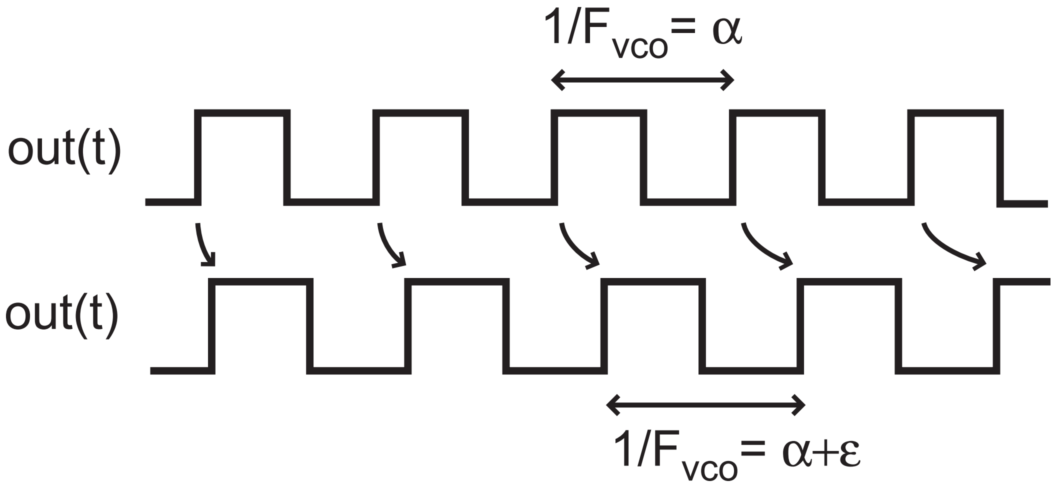
Model for Voltage to Phase Mapping of VCO

$$F_{out}(t) = K_v v_{in}(t)$$

- Phase is more convenient than frequency for analysis
  - The two are related through an integral relationship

$$\Phi_{out}(t) = \int_{-\infty}^{t} 2\pi F_{out}(\tau)d\tau = \int_{-\infty}^{t} 2\pi K_v v_{in}(\tau)d\tau$$

- Intuition of integral relationship between frequency and phase



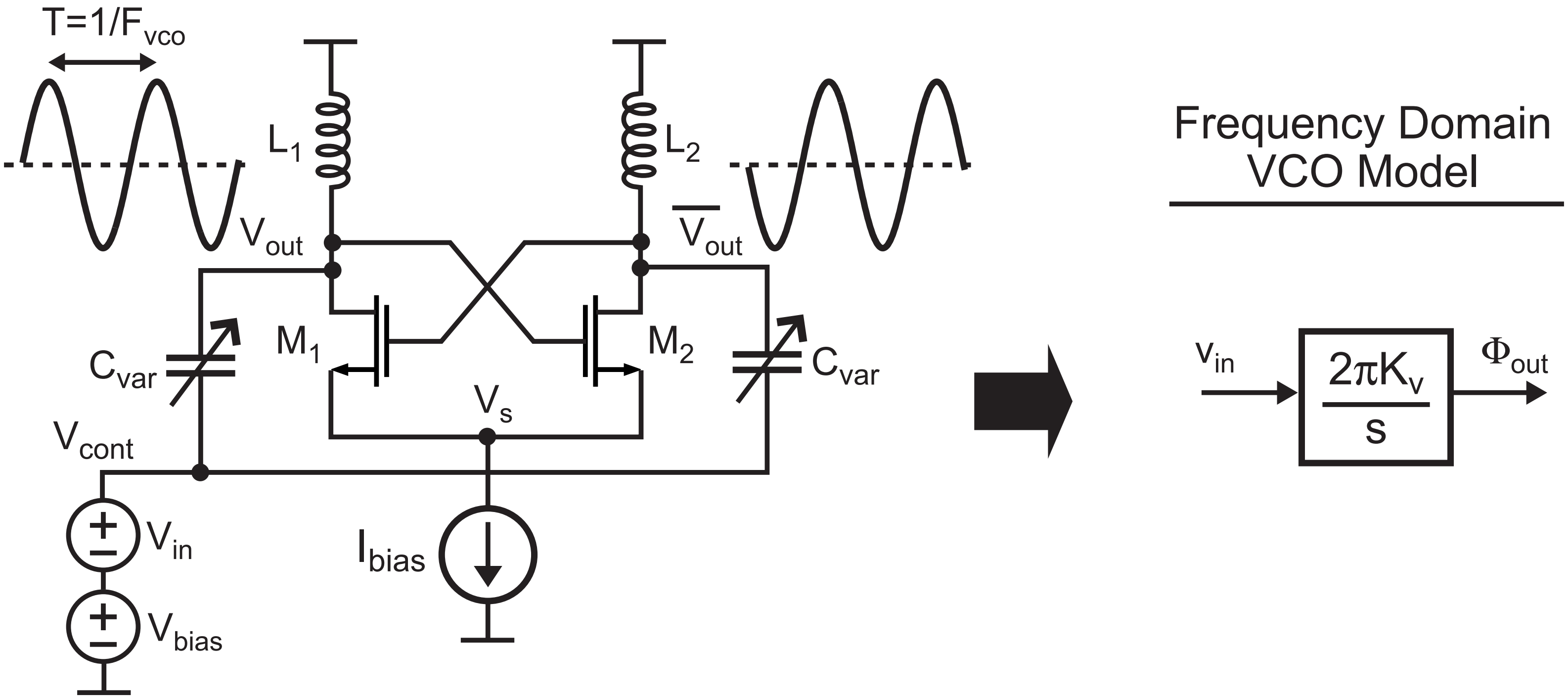
Frequency Domain Model of VCO

- **Take Laplace Transform of phase relationship**

$$\Phi_{out}(t) = \int_{-\infty}^{t} 2\pi K_v v_{in}(\tau)d\tau$$

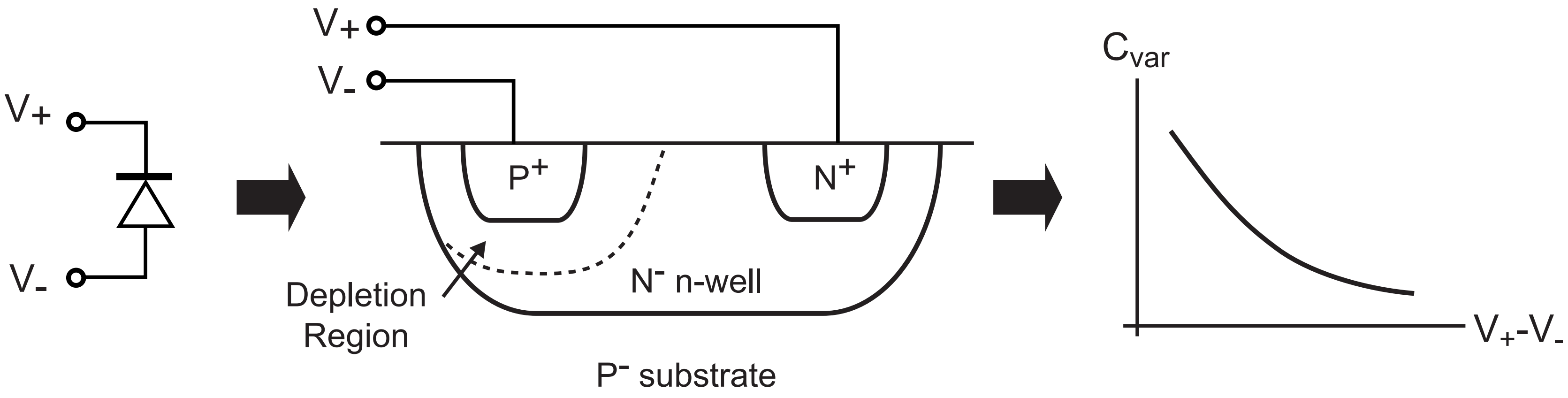
$$\Rightarrow \quad \Phi_{out}(s) = 2\pi K_v v_{in}(s)$$

  - **Note that K_v is in units of Hz/V**



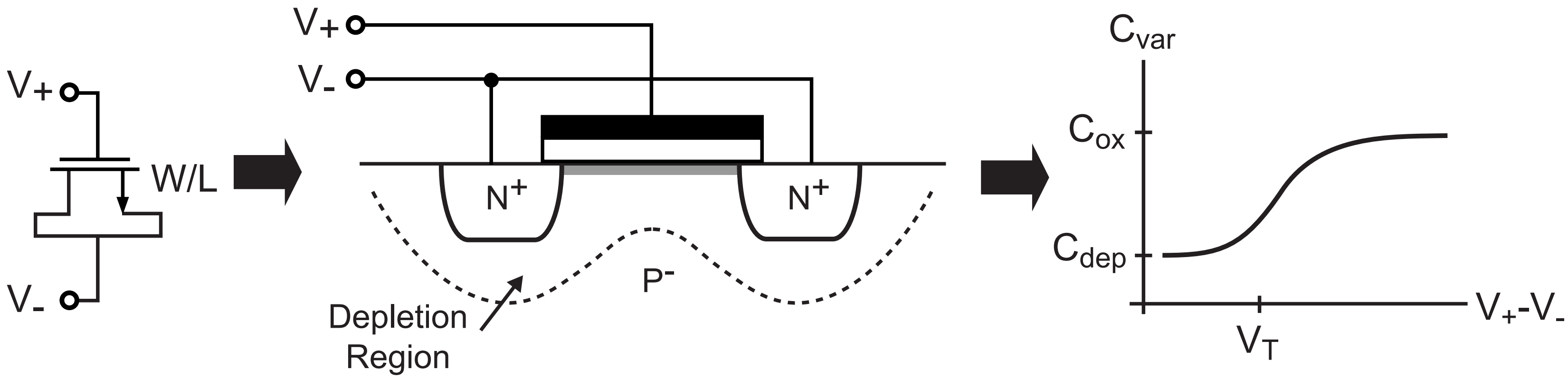
Varactor Implementation – Diode Version

- **Consists of a reverse biased diode junction**
  - **Variable capacitor formed by depletion capacitance**
  - **Capacitance drops as roughly the square root of the bias voltage**
- **Advantage – can be fully integrated in CMOS**
- **Disadvantages – low Q (often < 20), and low tuning range (± 20%)**

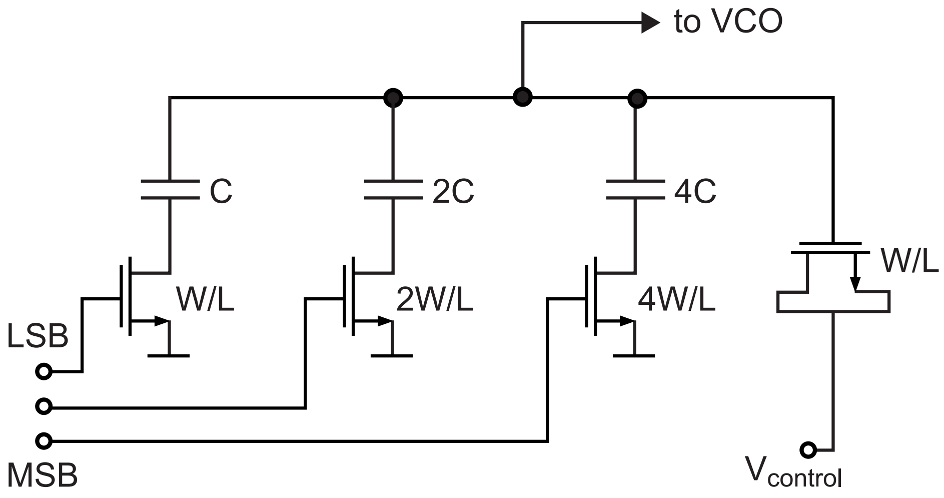


A Recently Popular Approach – The MOS Varactor

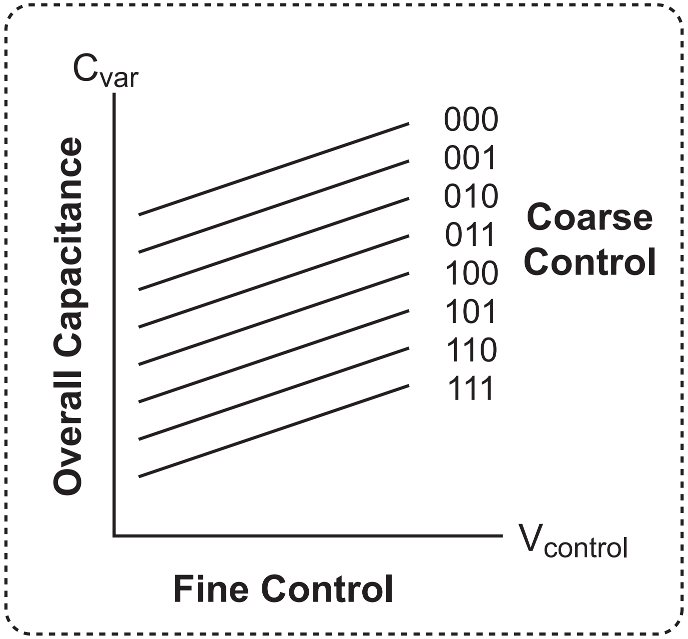
- **Consists of a MOS transistor (NMOS or PMOS) with drain and source connected together**
  - **Abrupt shift in capacitance as inversion channel forms**
- **Advantage – easily integrated in CMOS**
- **Disadvantage – Q is relatively low in the transition region**
  - **Note that large signal is applied to varactor – transition region will be swept across each VCO cycle**



A Method To Increase Q of MOS Varactor

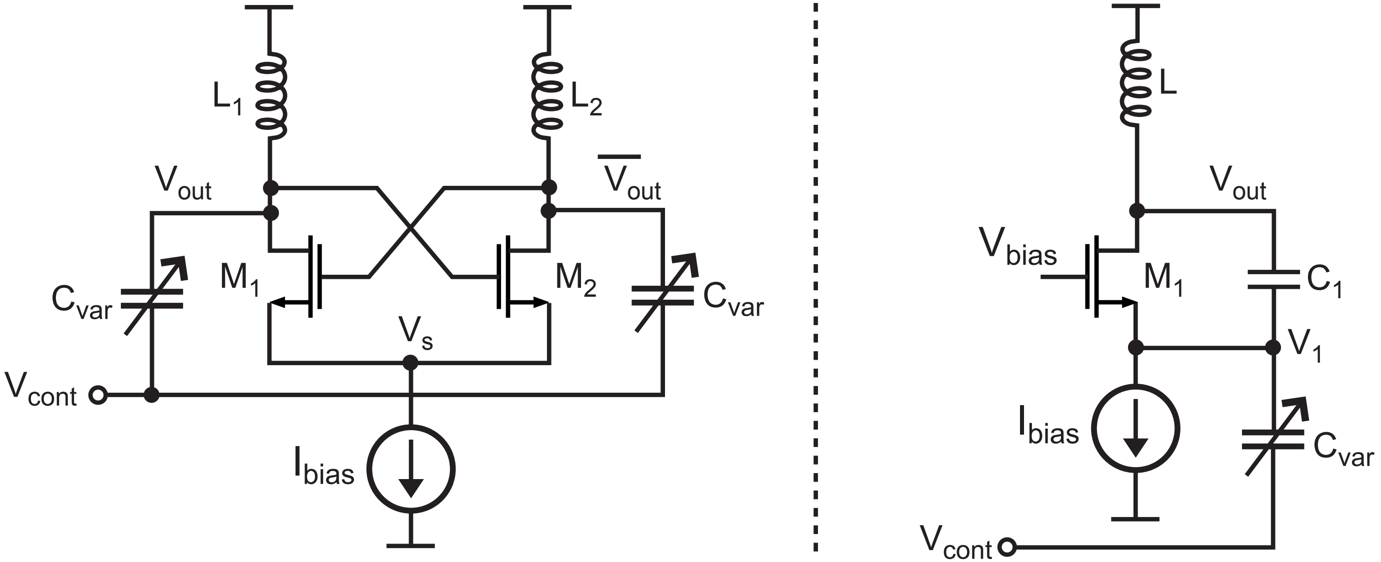


Coarse Control **Fine Control**



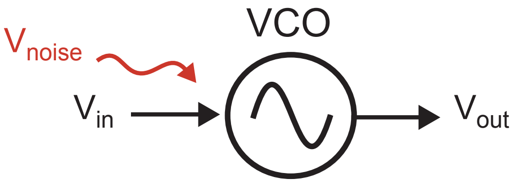
- **High Q metal caps are switched in to provide coarse tuning**
- **Low Q MOS varactor used to obtain fine tuning**
- **See Hegazi et. al., “A Filtering Technique to Lower LC Oscillator Phase Noise”, JSSC, Dec 2001, pp 1921-1930**

Supply Pulling and Pushing

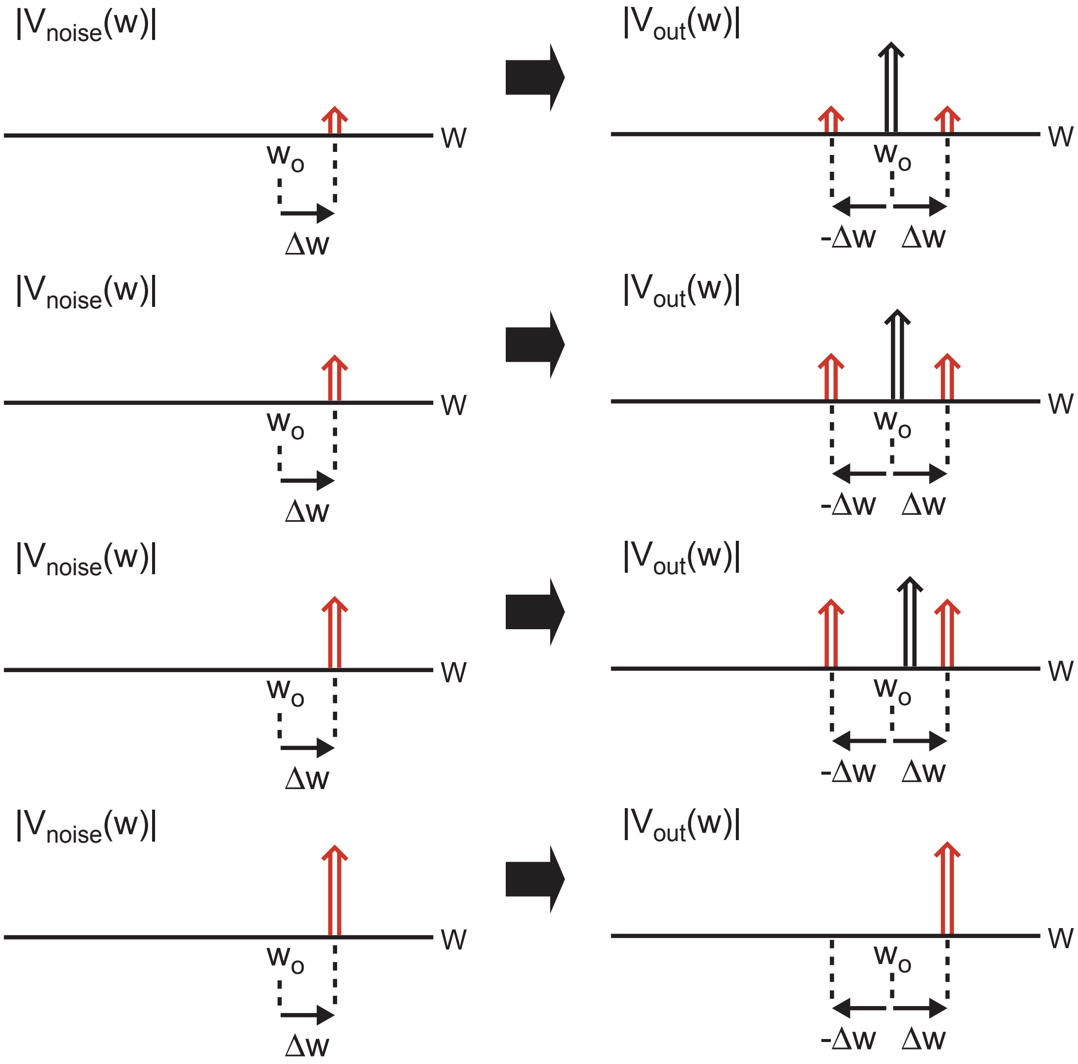


- Supply voltage has an impact on the VCO frequency
  - Voltage across varactor will vary, thereby causing a shift in its capacitance
  - Voltage across transistor drain junctions will vary, thereby causing a shift in its depletion capacitance
- This problem is addressed by building a supply regulator specifically for the VCO

Injection Locking

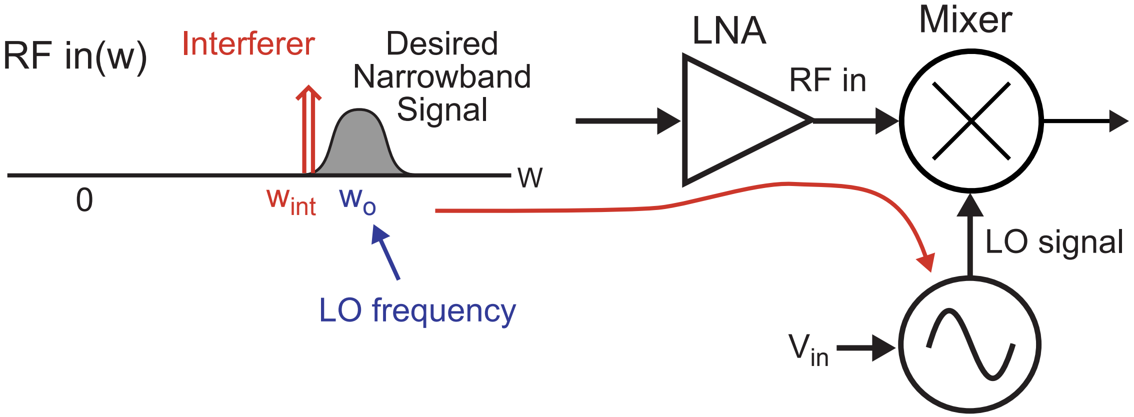


- **Noise close in frequency to VCO resonant frequency can cause VCO frequency to shift when its amplitude becomes high enough**



Example of Injection Locking

- **For homodyne systems, VCO frequency can be very close to that of interferers**



  - **Injection locking can happen if inadequate isolation from mixer RF input to LO port**
- **Follow VCO with a buffer stage with high reverse isolation to alleviate this problem**