6. 776
High Speed Communication Circuits and Systems
Lecture 15
VCO Examples
Mixers

Massachusetts Institute of Technology

March 31, 2005

Voltage Controlled Oscillators (VCO's)
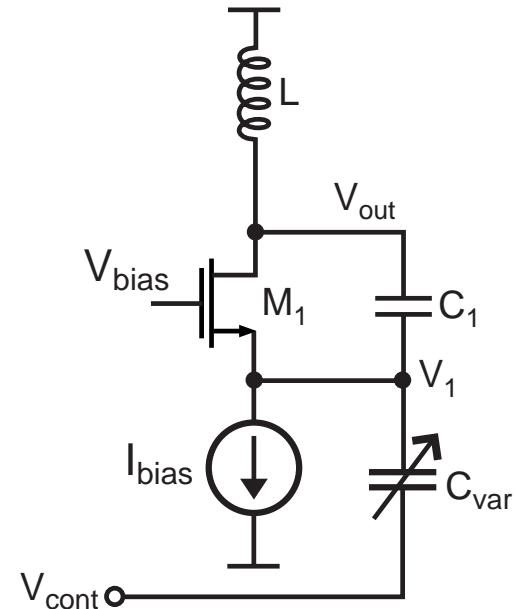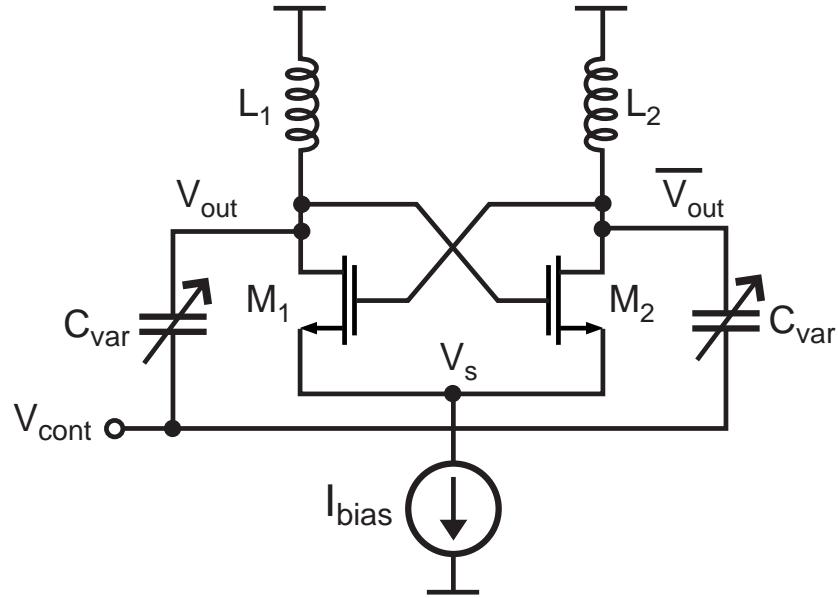
- **Include a tuning element to adjust oscillation frequency**
  - **Typically use a variable capacitor (varactor)**
- **Varactor replaces (part of) fixed capacitance**
  - **Note that some fixed capacitance cannot be removed (transistor junctions, interconnect, etc.)**
    - Fixed cap lowers frequency tuning range

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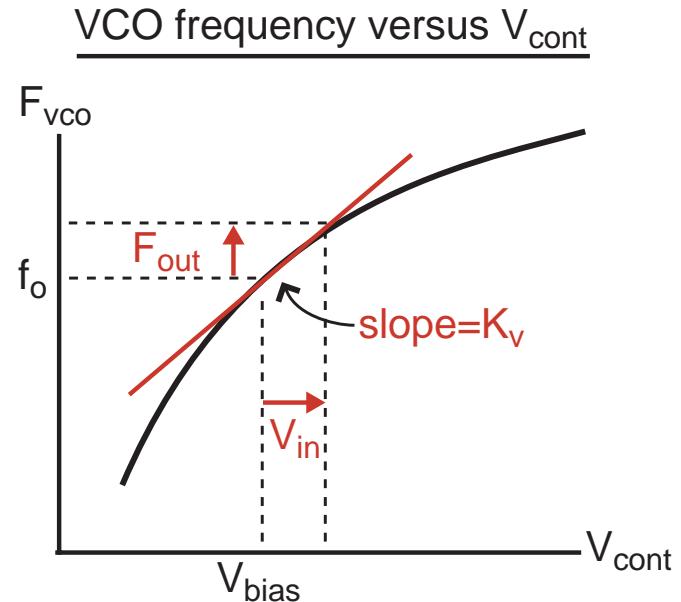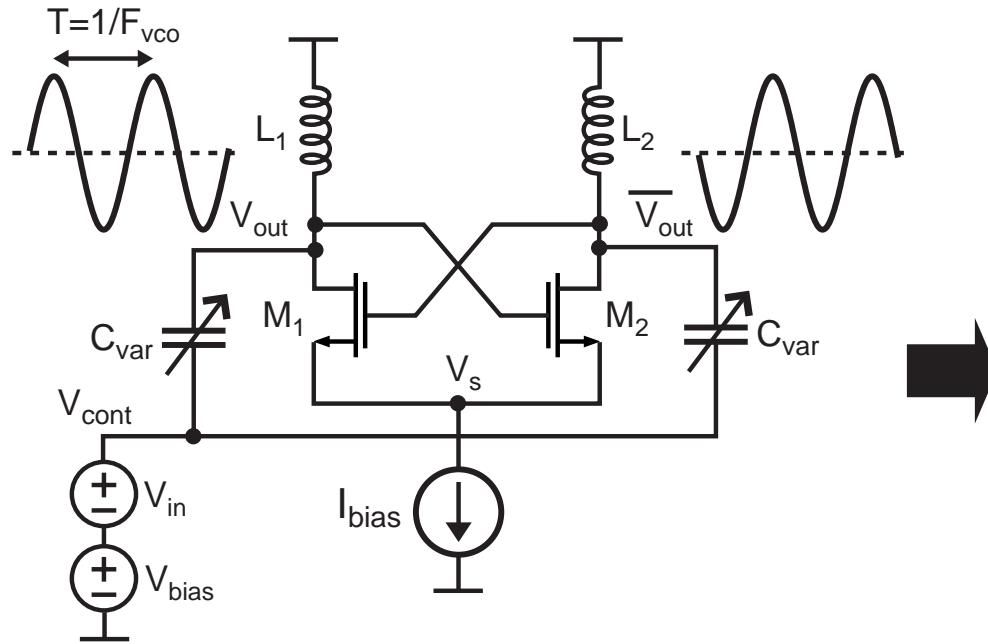
- **Model VCO in a small signal manner by looking at deviations in frequency about the bias point**
  - **Assume linear relationship between input voltage and output frequency**

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

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**

$1/F_{vco} = \alpha$

out(t)

out(t)

$1/F_{vco} = \alpha + \varepsilon$
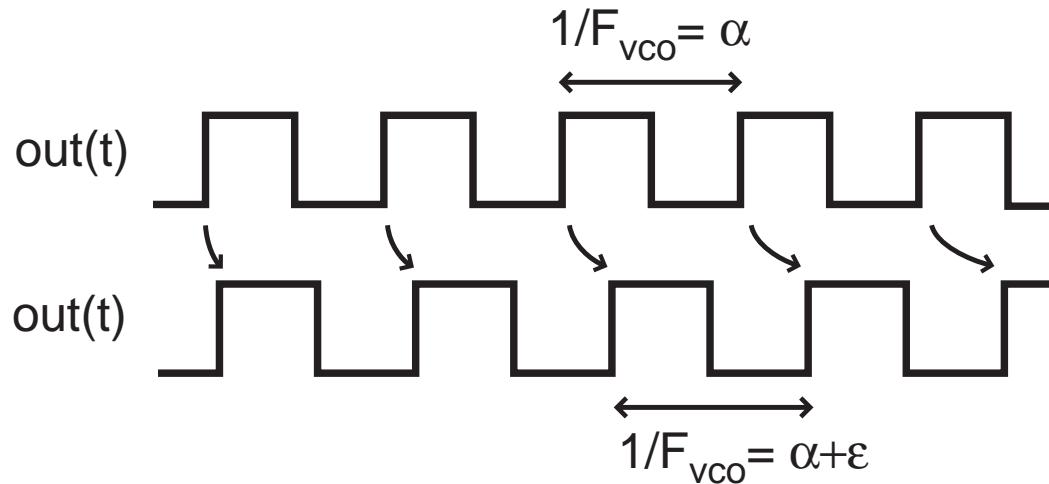
Frequency Domain Model of VCO

- **Take Laplace Transform of phase relationship**

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

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

- **Note that K_v is in units of Hz/V**
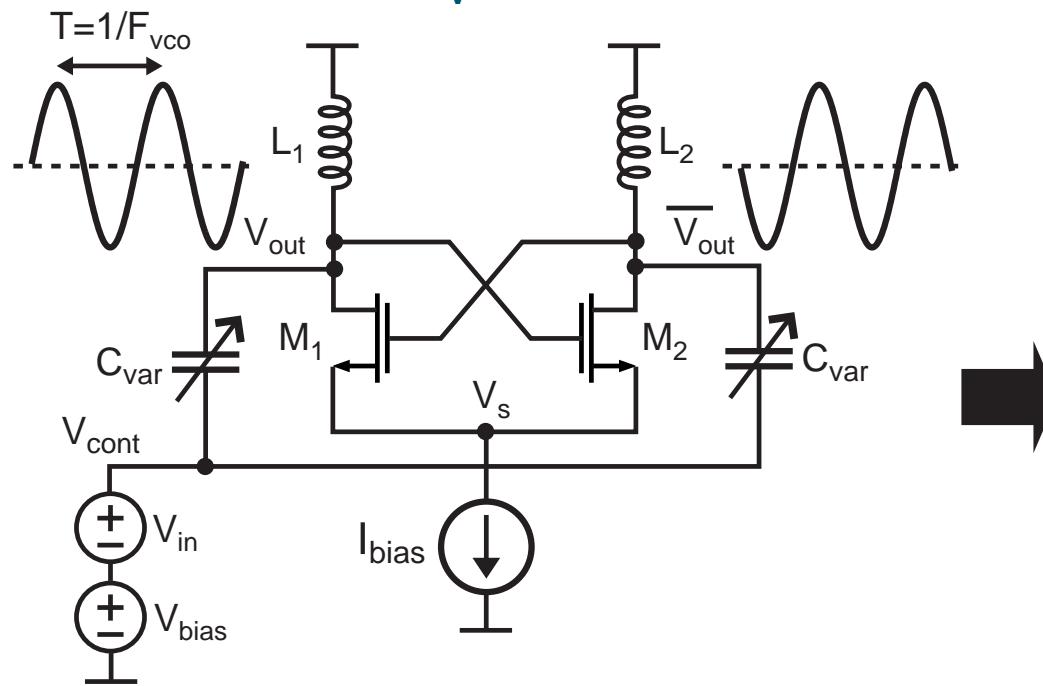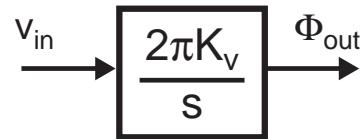
# *Varactor Implementation – Diode Version*

- **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 ($\pm$ 20%)**
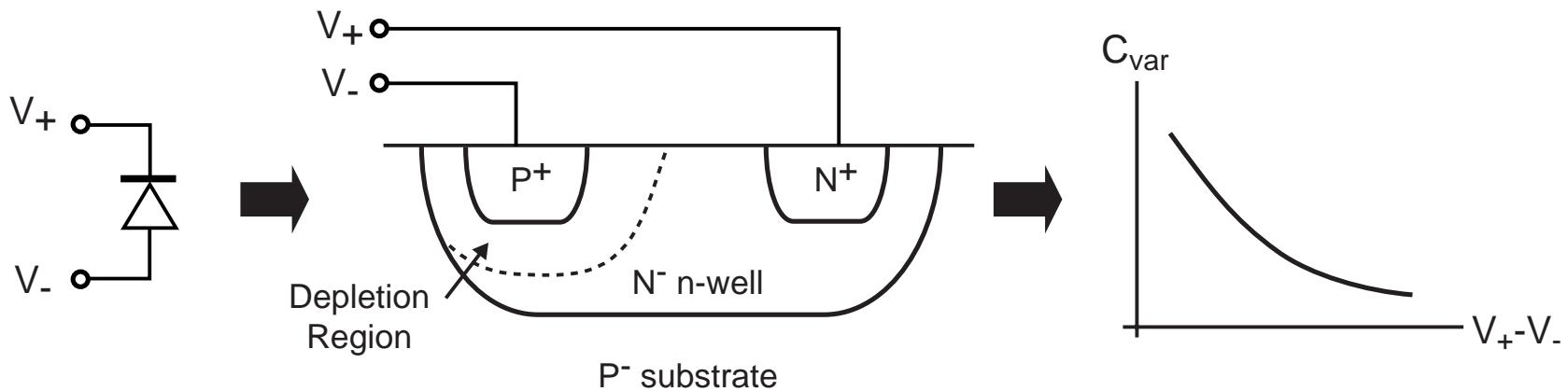
A Recently Popular Approach – The MOS Varactor

- **Consists of a MOS transistor (NMOS or PMOS) with drain and source connected together**
  - **Abrupt change 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**
- **Watch out for gate-to-bulk capacitance!**

# A Recently Popular Approach – The MOS Varactor
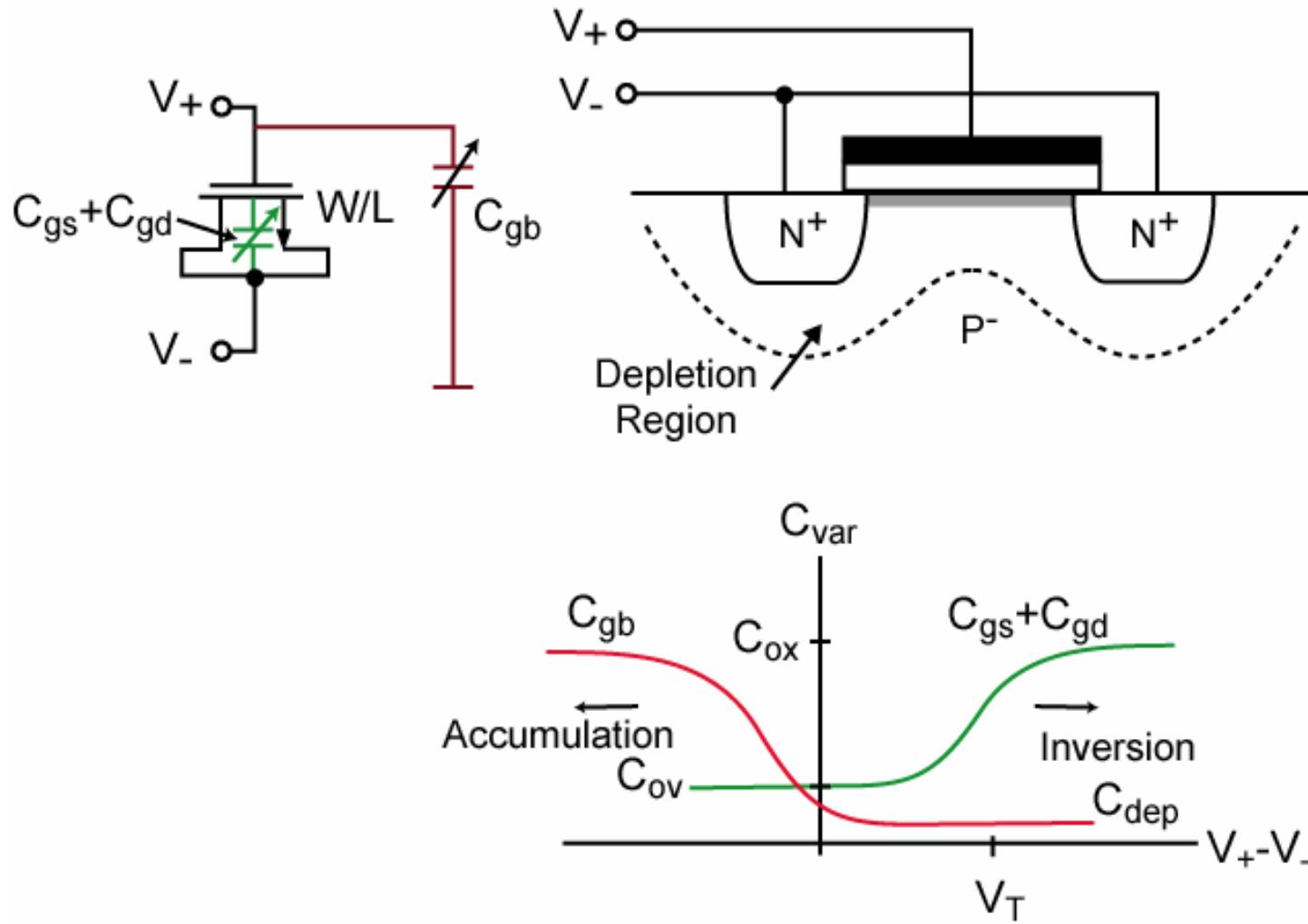
A Method To Increase Q of MOS Varactor
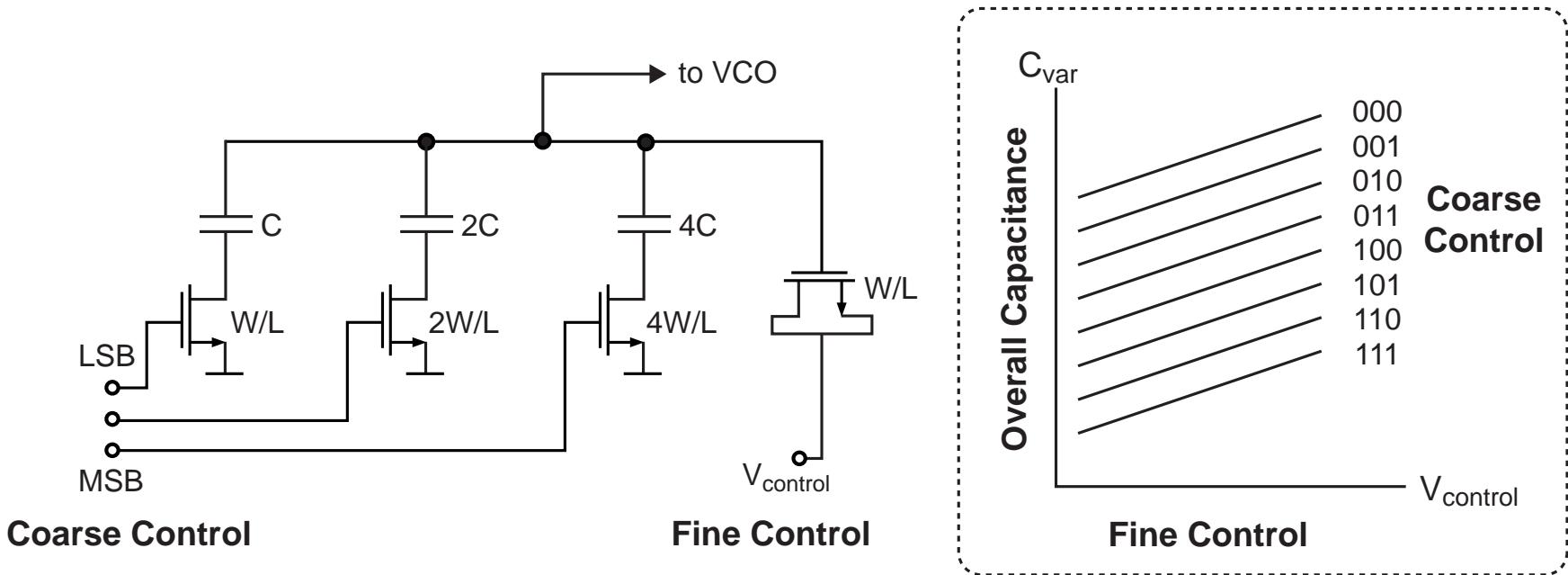
- **High Q metal caps are switched in to provide coarse tuning**
- **Low Q MOS varactor used to obtain fine tuning**
- **See Hegazi et. al., "A Filtering Technique to Lower LC Oscillator Phase Noise", JSSC, Dec 2001, pp 1921-1930**

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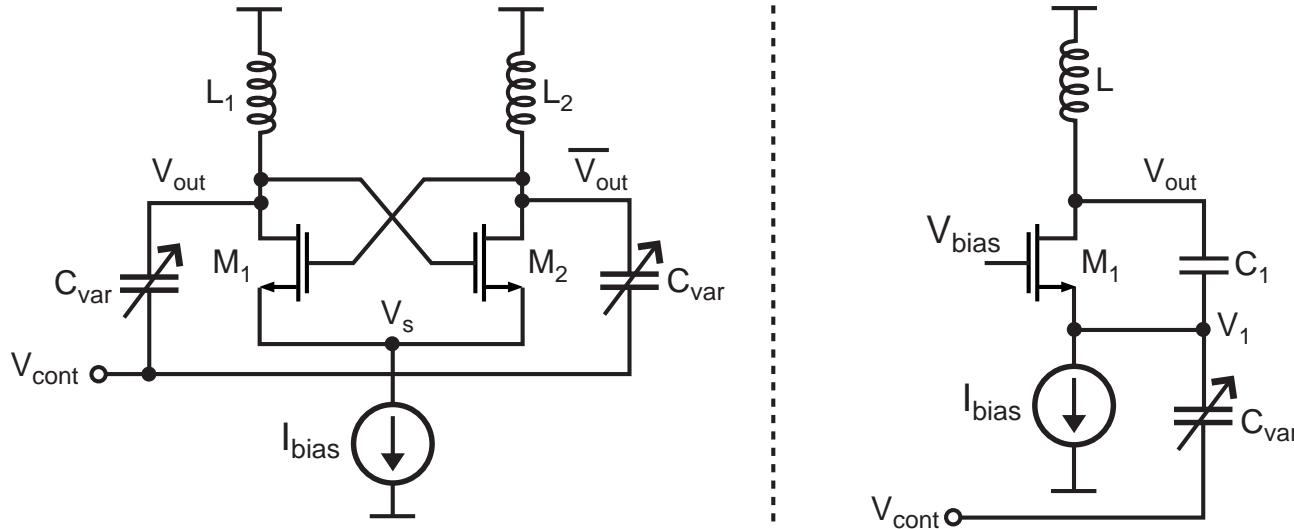
- **Supply voltage has an impact on the VCO frequency**
  - **Voltage across varactor will vary, thereby causing a shift in its capacitance**
  - **Voltage across transistor drain junctions will vary, thereby causing a shift in its depletion capacitance**
- **This problem is addressed by building a supply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

Injection Locking in Oscillators

- **Recall Barkhausen's Criteria**
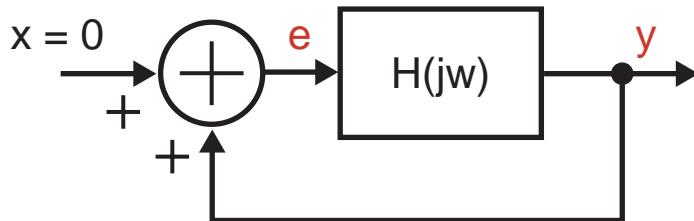
- **Closed loop transfer function**

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

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

$$H(jw_o) = 1$$
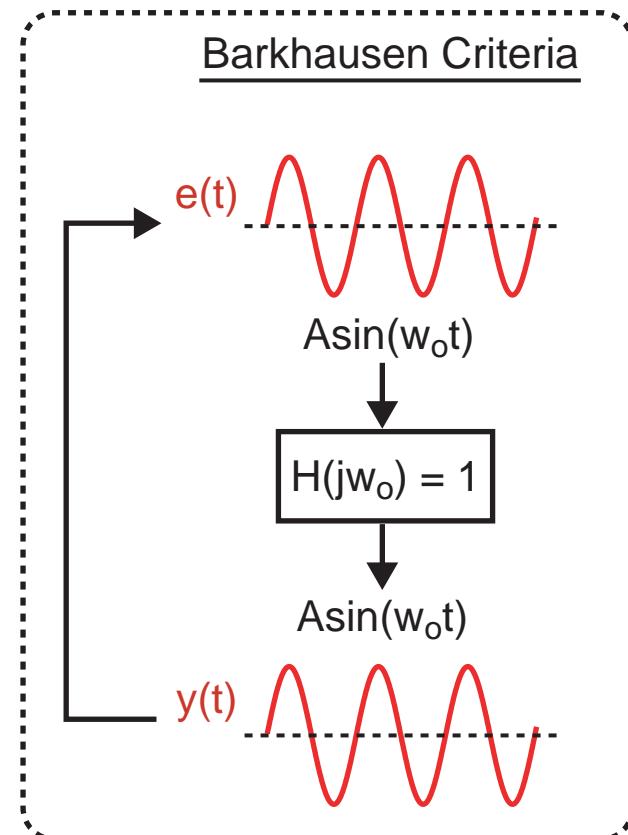
Injection Locking Mechanism

- **With the input x=0, the self-sustaining oscillation occurs at ω_o because**

$$|G(jw_o)| = \infty$$

- **At frequency small deviation $\Delta\omega$ away from ω_o, the magnitude of $G(j\omega)$ is still very large**

- **So, what if the input x is a nonzero signal at $\omega_o+\Delta\omega$?**

- **If the circuit is purely linear, the output y will contain both the oscillation at ω_o and the amplified input at $\omega_o+\Delta\omega$ (superposition)**

$|G(j\omega)|$

$\omega_0 \quad \omega_0+\Delta\omega$
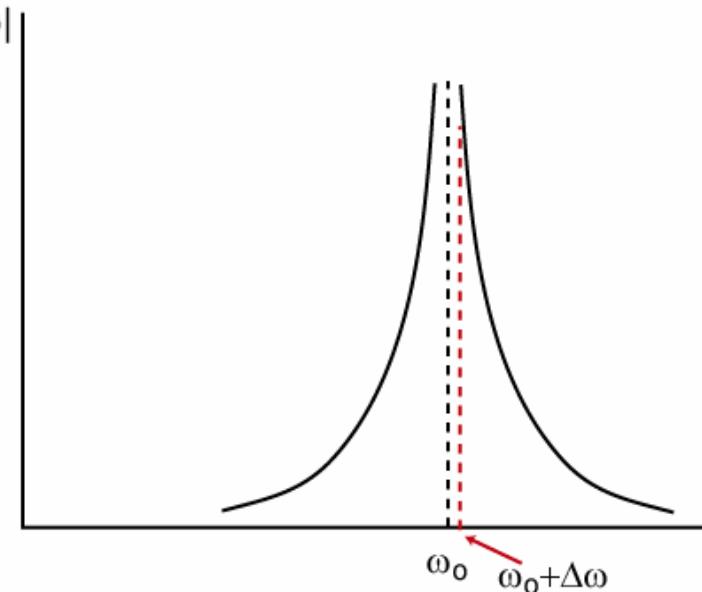
Injection Locking, Cnt'd
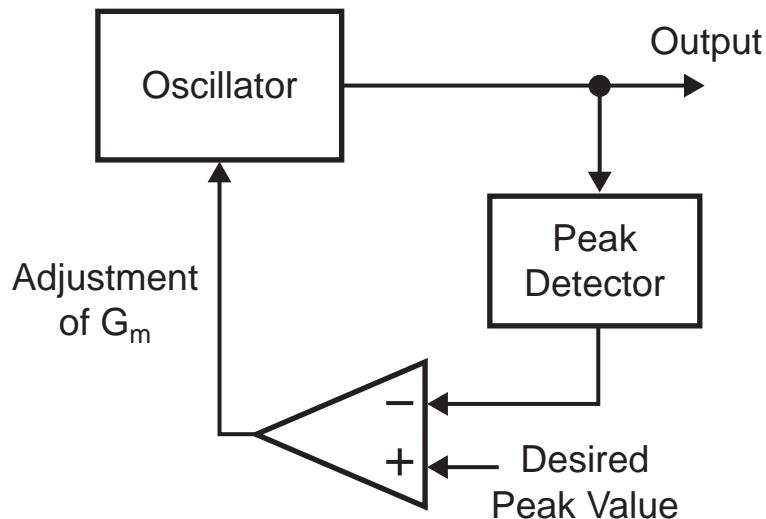
- **In a real oscillator, the transfer function is non-linear to keep the amplitude constant (either by amplitude feedback or saturating G_m characteristic)**

- **But, let's first look at what happens if the oscillator transfer function is linear and if a small amplitude signal is injected at the input x**

Intuitive Look at Injection Locking, Linear Case

- **Let's conceptually make the oscillator transfer function linear by letting the output reach a desired amplitude (say 1V) and disengaging the amplitude feedback after sampling and holding the G_m adjustment voltage at that level**

- **The value of G_m is precisely that would make $|G(jw_o)| = \infty$ at that point**

- **Assuming nothing drifts, the output would be a constant amplitude oscillation at ω_o**

- **Next, let's see what happens if we inject a sinusoidal signal with a small amplitude, say 10mV, at $\omega_o + \Delta\omega$ at input x**

- **$|G(j\omega)|$ is very large at this frequency – let's say $|G(j\omega)| = 10,000$ at $\omega = \omega_o + \Delta\omega$**

- **The output will be the superposition of 1V sinusoid at ω_o and a 100V sinusoid at $\omega_o + \Delta\omega$**

Intuitive Look at Injection Locking, Nonlinear Case

- **If the amplitude feedback is re-engaged, it will lower G_m to keep the *total* amplitude at the desired 1V level.**

- **This value of G_m would adjusted be far below what's necessary to sustain oscillation at ω_o**

- **Thus, *only* the sinusoid at $\omega_o + \Delta\omega$ will appear at the output with an amplitude of 1V. The VCO frequency is hence locked to the input frequency $\omega_o + \Delta\omega$ rather than oscillating at the free running frequency of ω_o**

- **The injection locking phenomenon can be exploited as an alternative to phase-locked loops (See Tom Lee's book, pp563-566, or p439, 1st, ed.)**

- **Otherwise, the injection locking is troublesome**

# *Example of Undesired Injection Locking*

- **For homodyne systems, VCO frequency can be very close to that of interferers**
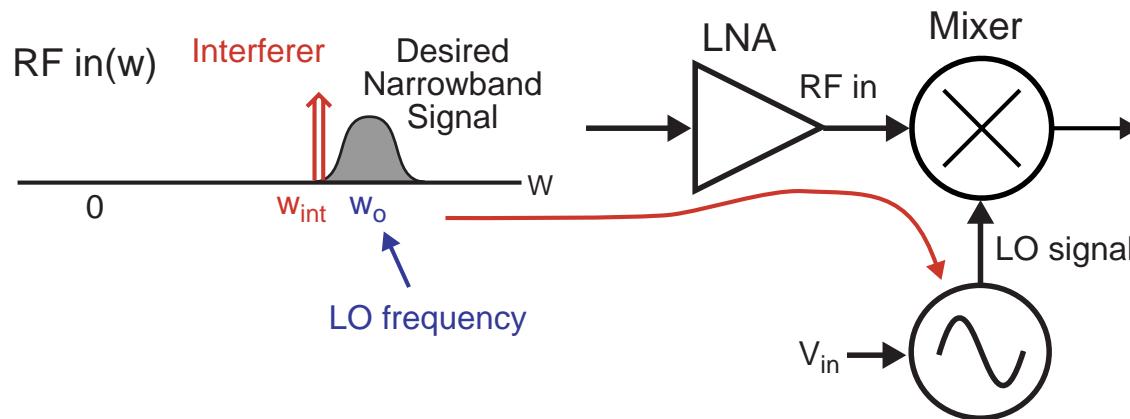
   - **Injection locking can happen if inadequate isolation from mixer RF input to LO port**
- **Follow VCO with a buffer stage with high reverse isolation to alleviate this problem**

Recent VCO Techniques

- **G_m-boosted VCO for lower phase noise**
 **Recall g_m-boosted LNA lowered noise factor:**
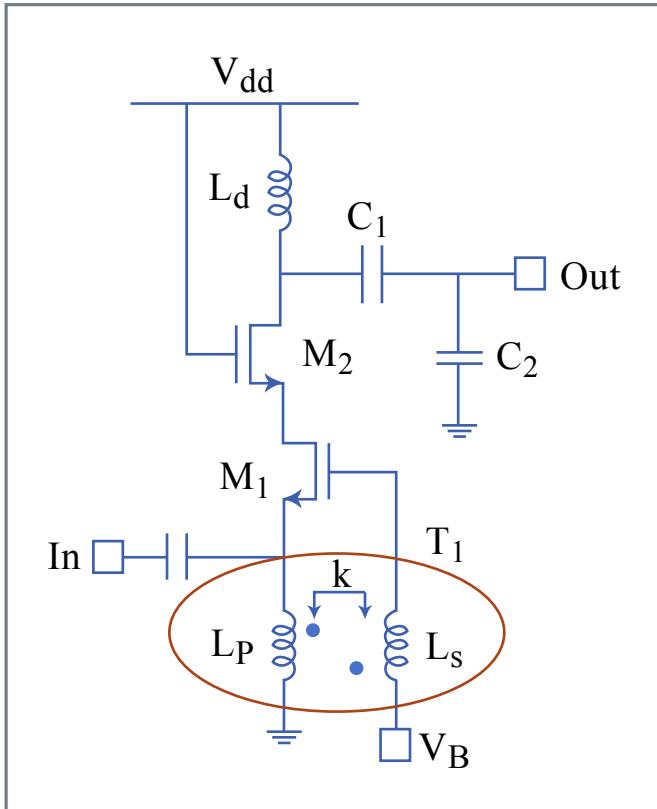
$$F = 1 + \frac{\gamma}{\alpha} \cdot \frac{1}{1 + nk}$$

Figure by MIT OCW.

The apparent g_m boost is is the result of the gate and source having 180° out-of-phase waveforms (it increases V_{gs}).

Gm-Boosted VCO

- **Similar concept can be employed for VCO's to lower phase noise.**
- **Transformer coupling is possible, but takes up area.**
- **Can boost g_m just by feeding output back to source**
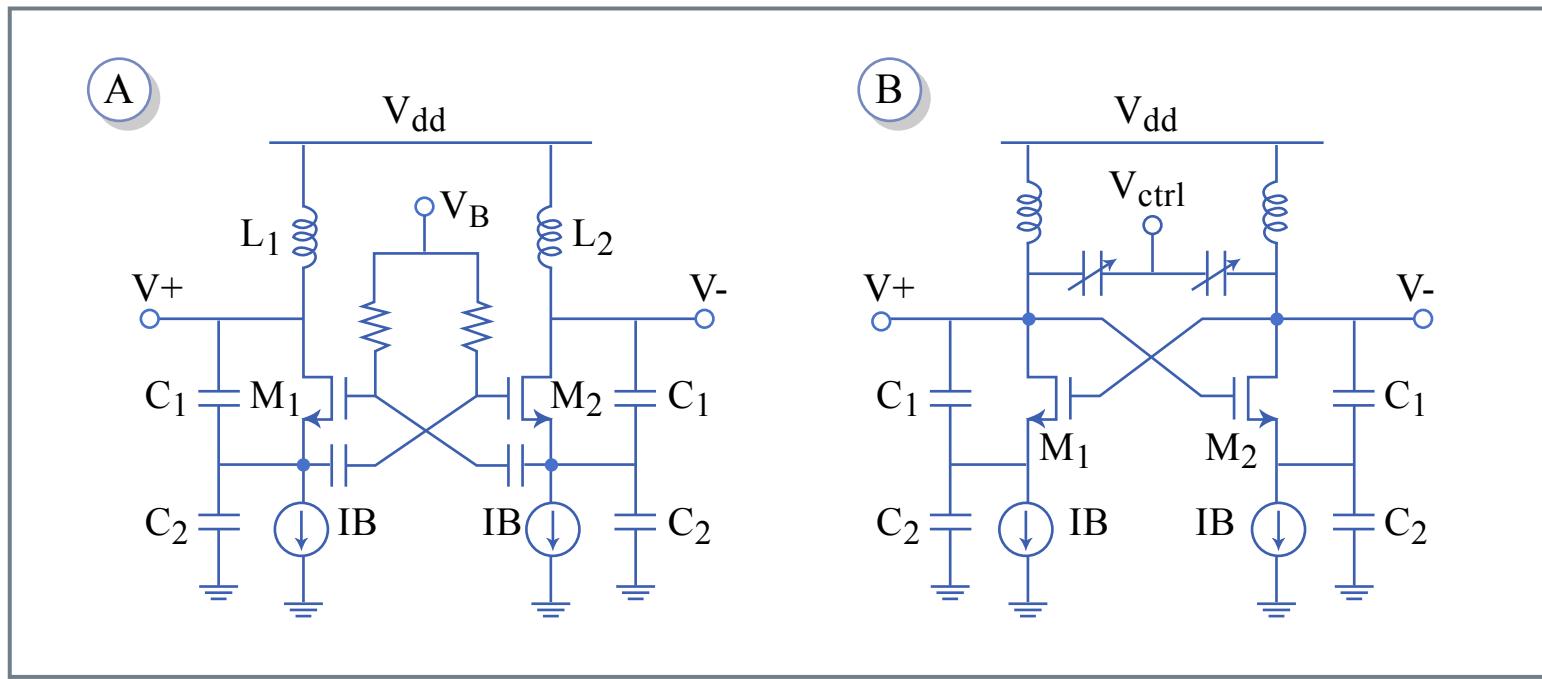
basic concept   self-biased VCO

Figure by MIT OCW.

See Xiaoyong Li et. al., "Low-Power gm-boosted LNA and VCO Circuits in 0.18μm CMOS" 2005 ISSCC Digest of Technical Papers pp. 534-353

Wide Tune Range VCO

- **Davide Guermandi , et. al "A 0.75 to 2.2GHz Continuously-Tunable Quadrature VCO," Digest of Technical Papers, 2005 ISSCC pp 536-537**
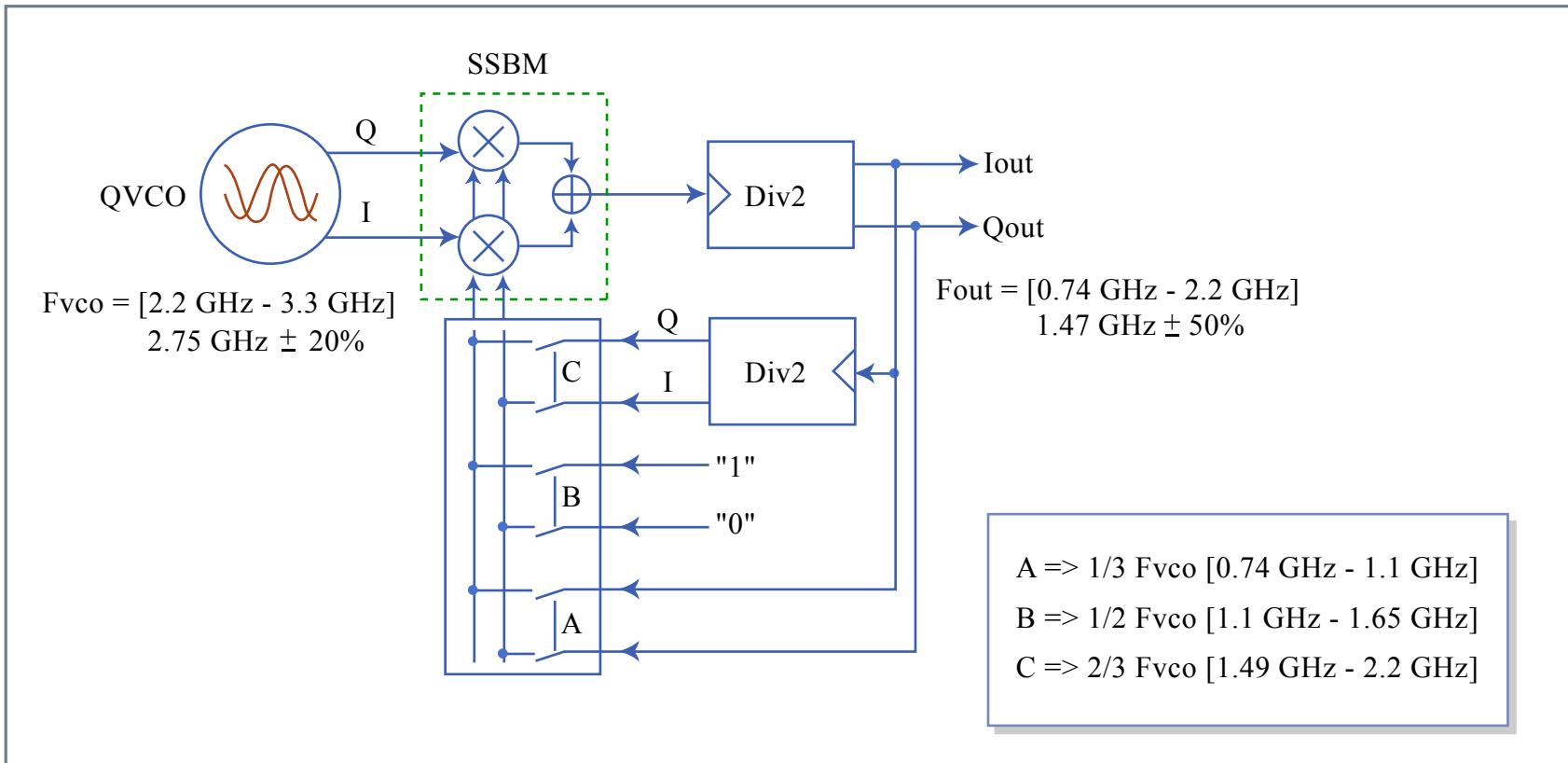

Figure by MIT OCW.

Wide Tune Range VCO, Continued

■ VCO, Divider and SSBM Circuits
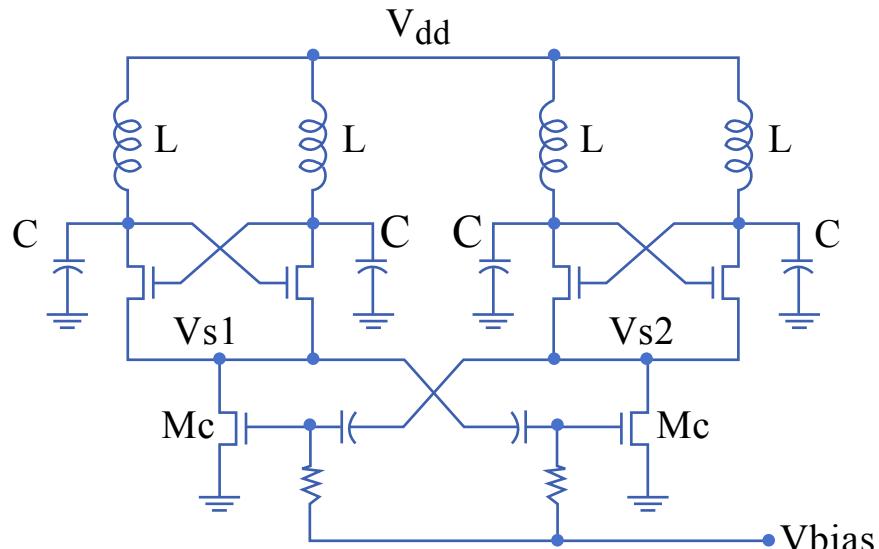
Quadrature VCO
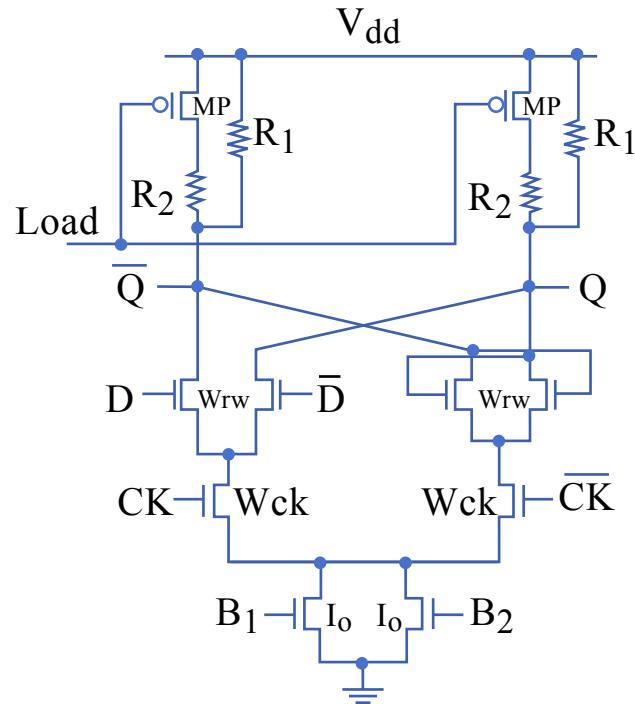
Balanced Modulator

Figure by MIT OCW.

Very High Frequency VCO
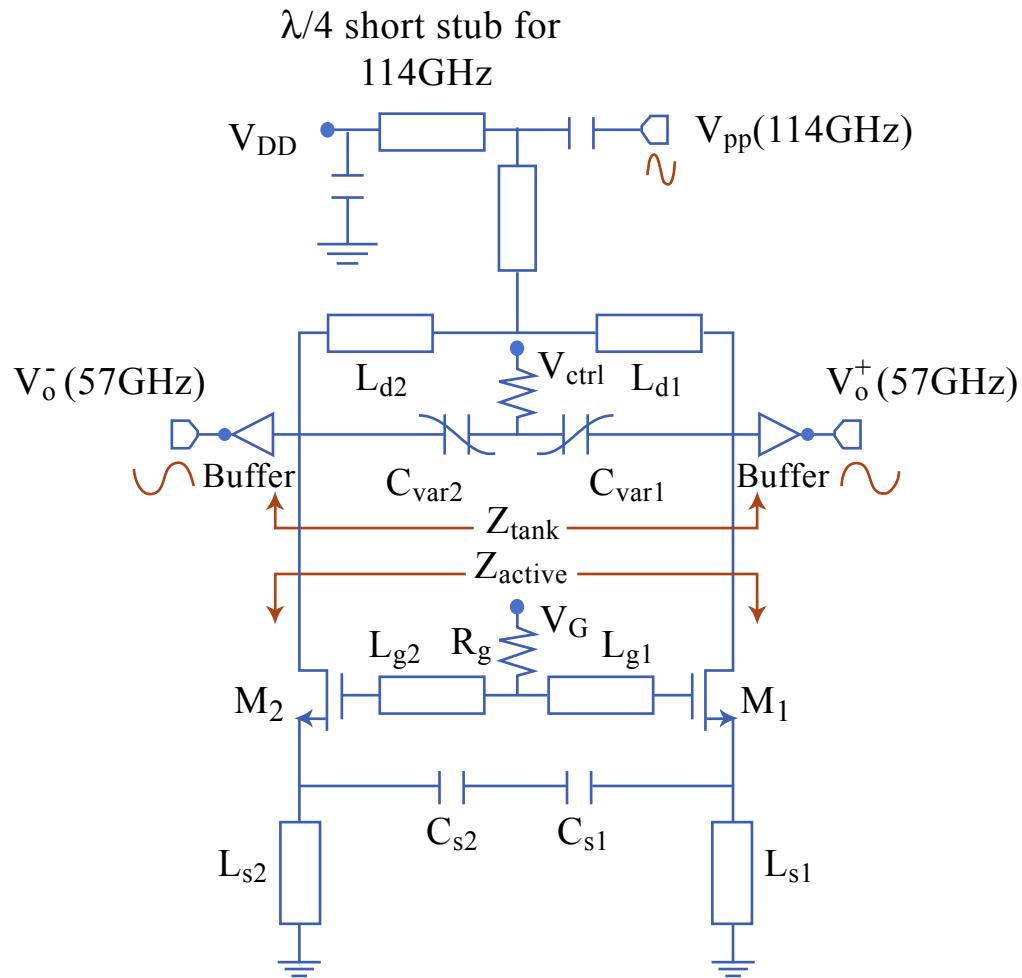
- **Ping Chen, et. al. "A 114GHz VCO in 0.13μm CMOS Technology," 2005 ISSCC Digest of Technical Papers pp. 404-405**

Figure by MIT OCW.

Recent VCO Techniques

- **R. Aparicio and A. Hajimiri, "Circular Geometry Oscillators," ISSCC 2004 Digest of Technical Papers, pp378-379**

Figure by MIT OCW.
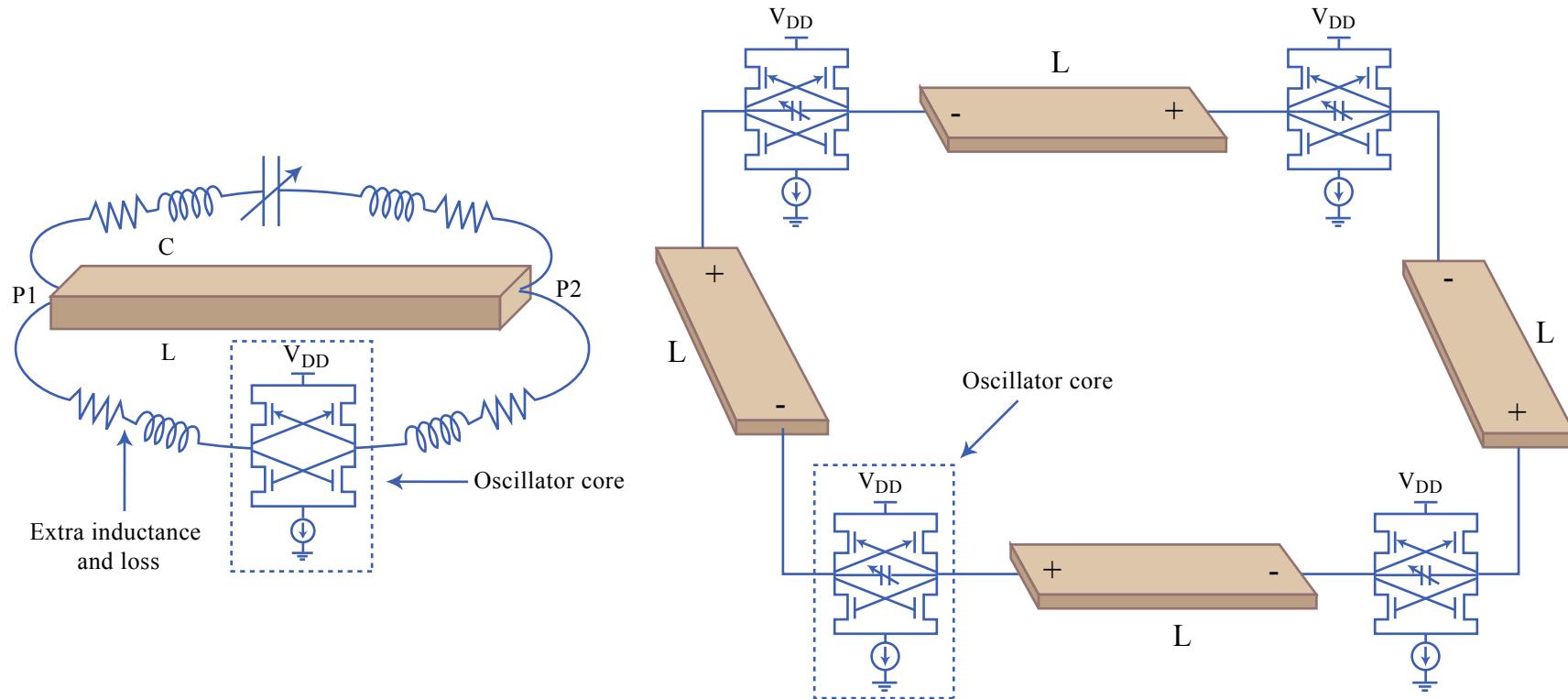
- **Slab inductors offer higher Q than spiral/circular inductors due to less current crowding and less substrate loss**
- **In a conventional oscillator topology, the interconnect adds undesired inductance with loss**
- **Circular geometry oscillator removes this problem**

Circular Oscillator Implementation
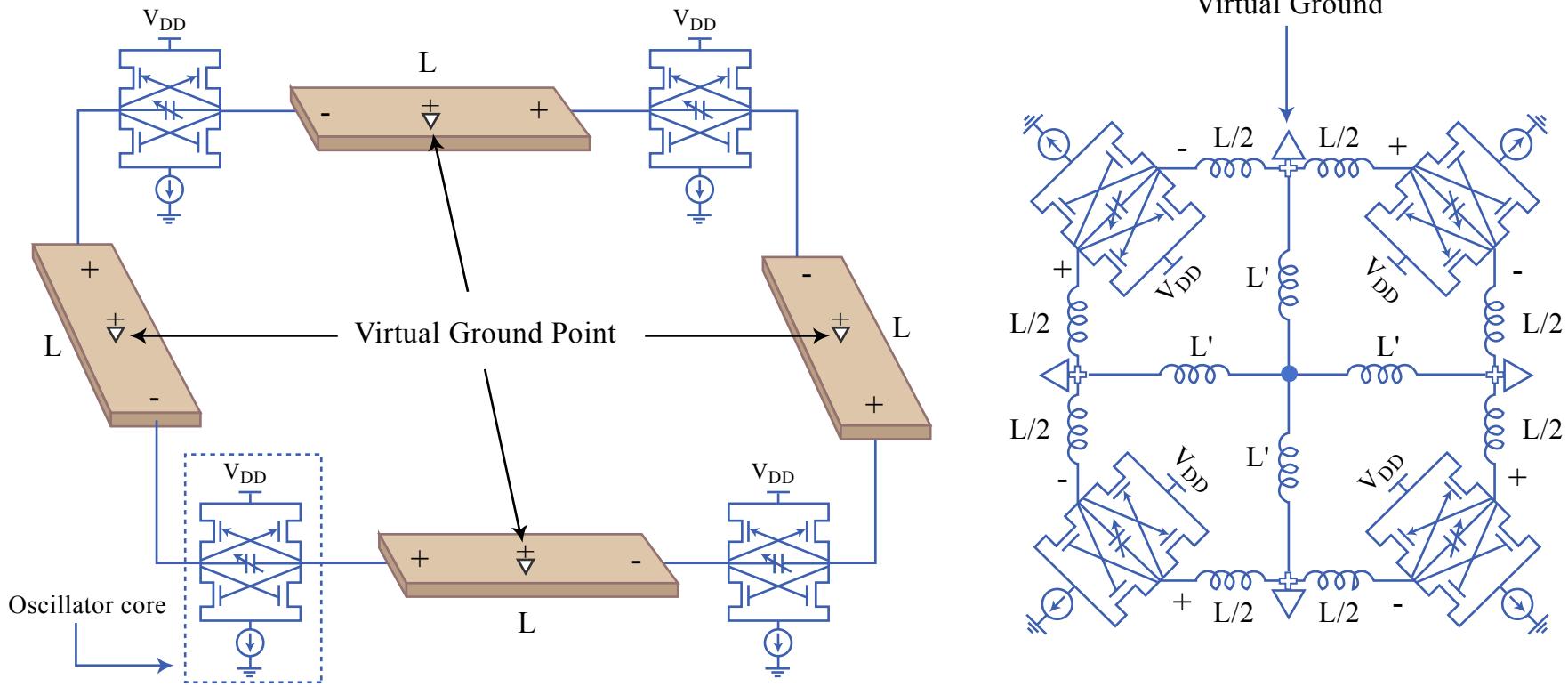
Figure by MIT OCW.

Shorts the outputs at DC to remove stable DC operating point
Shorts outputs at even harmonics to suppress undesired modes

Die Photo and Measured Results
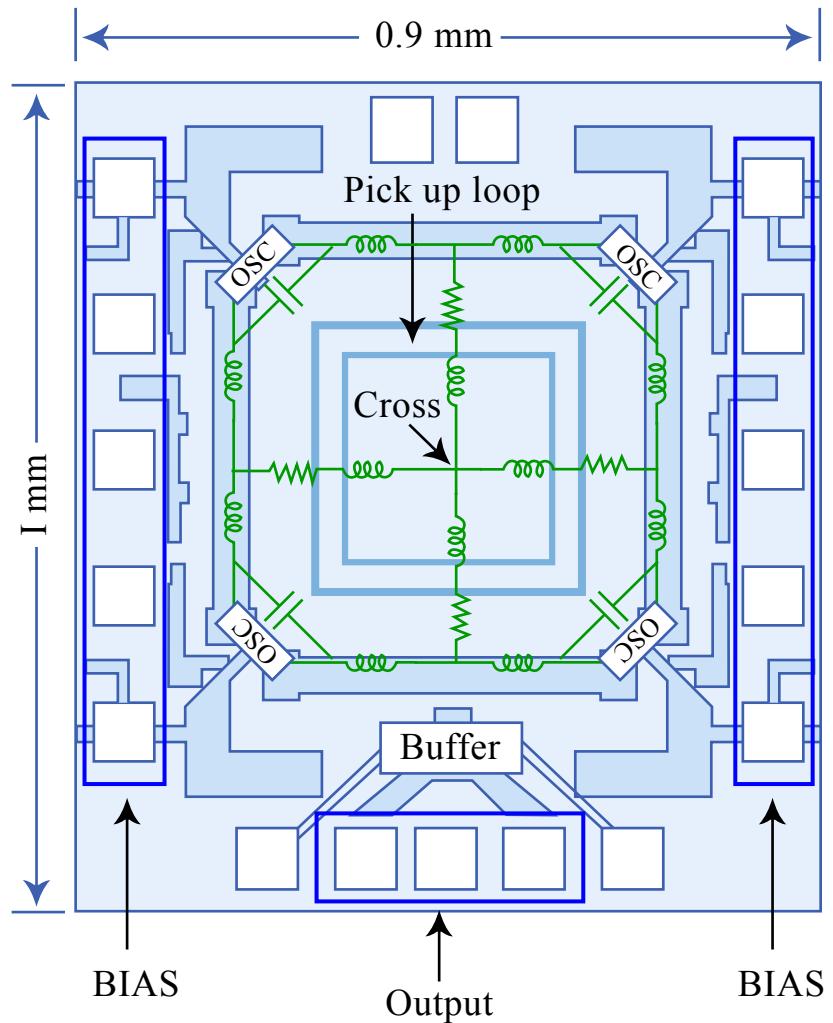
Circular-Geometry Oscillator	Single Frequency	VCO
Technology	SiGe 7HP (CMOS transistors only)	
Channel Length	0.18μm	
Center Frequency	5.35GHz	5.36GHz
Tuning Range	----	8.3%
Output Power	1dBm	
V_{dd}	1.4V	1.8V
I_{bias}	10mA	12mA

Figure by MIT OCW.

Circular Standing Wave Oscillator

D. Ham and W. Andress

**ISSCC 2004 Digest of Technical Papers, pp380-381**

Standing Wave Oscillators

λ/4 standing wave oscillator (SWO)**

Energy Injection

Reflection

Short

Reflective boundaries

Reflection

Reflection

Short

Short

λ/2 SWO [4][5]

Reflection

Reflection

Short

Short
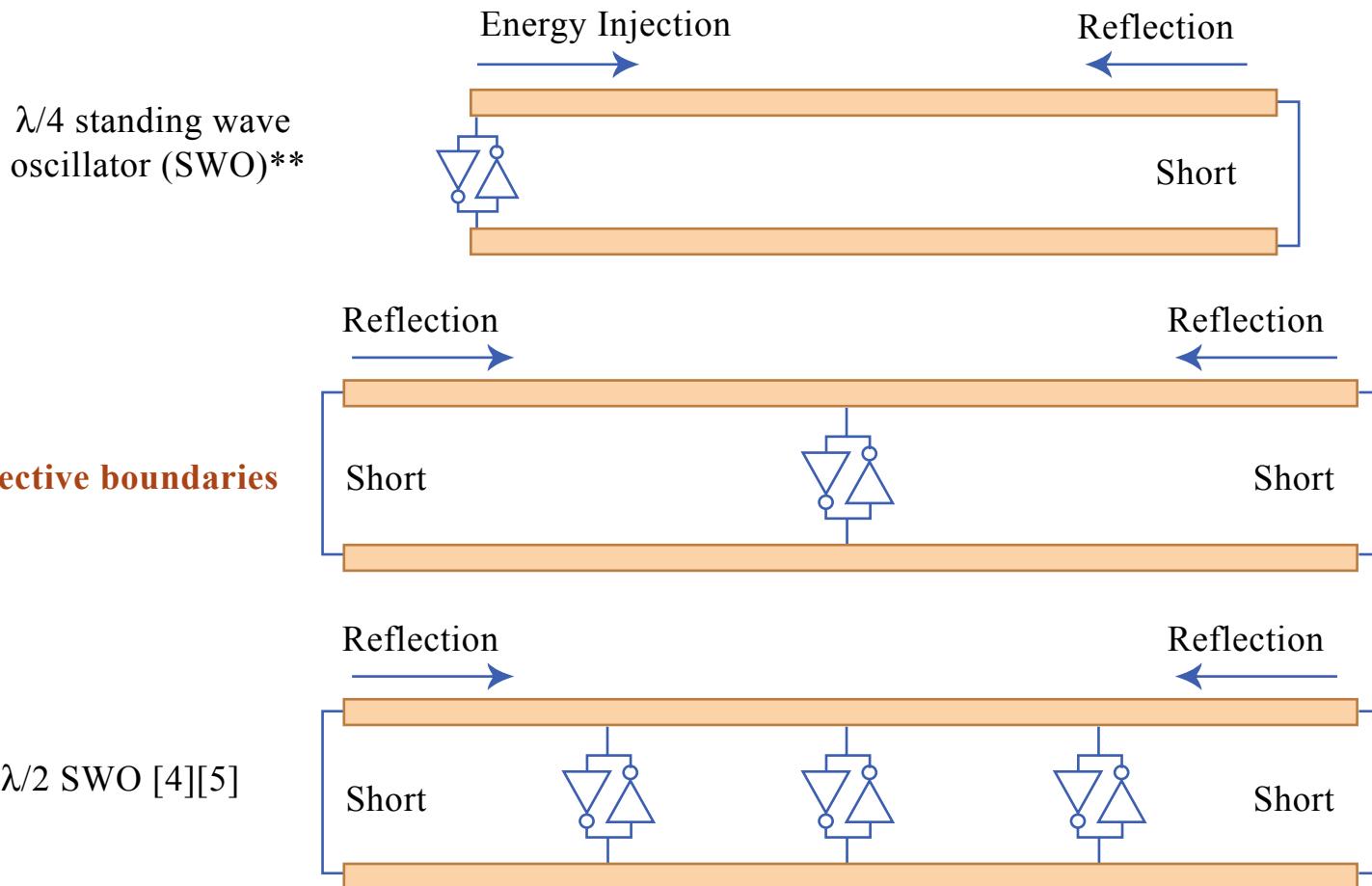
Figure by MIT OCW.

Ring Transmission Line Principle

ΔE
(energy injection)

$e^{-j\beta r\phi}$

$e^{j\beta r\phi}$

$\phi+2\pi$

ϕ

r

Differential ring t-line
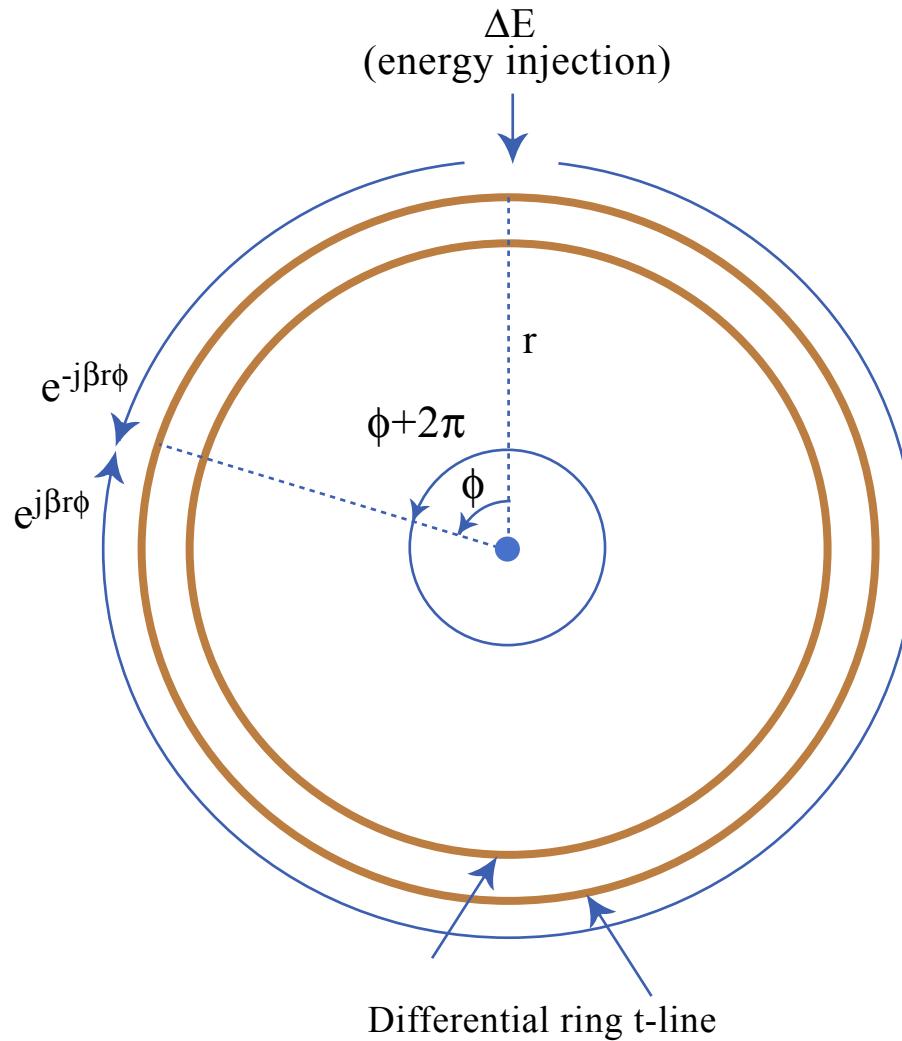
Wave superposition

$V(\phi) \sim e^{-j\beta r\phi} + e^{j\beta r\phi} \sim \cos(\beta r\phi)$

Standing wave formation

Periodic boundary condition

$V(\phi) = V(\phi+2\pi)$

Standing wave modes

$l = n\lambda \ (n = 1, 2, 3,....)$

Circular Standing Wave Oscillator (CSWO)

KEY

L: Loud

Q: Quiet

Even-mode suppression connection ----------

CSWO PSD at port T1-T2

After even-mode suppression
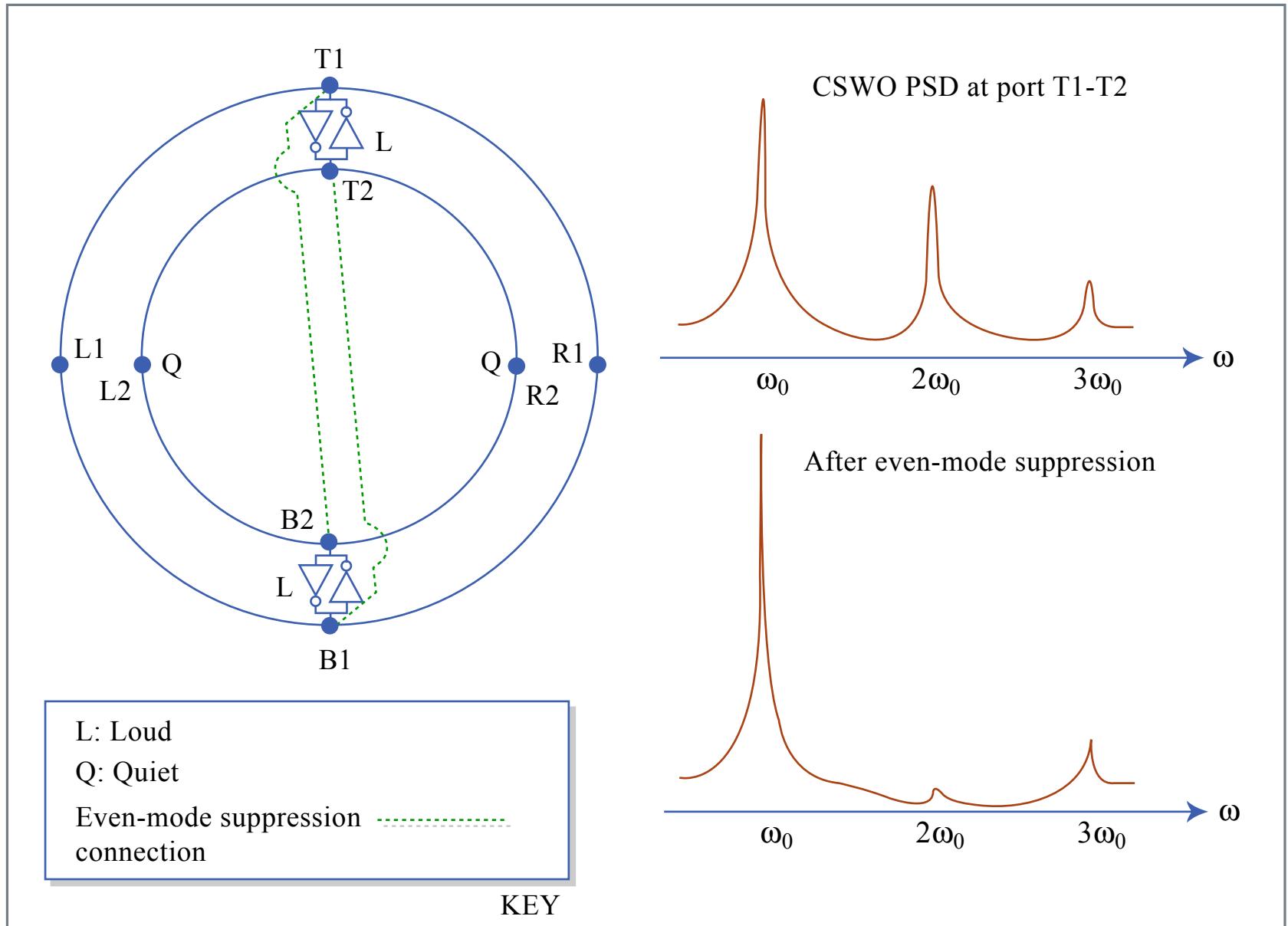
Die Photo and Measurement Set up

Agilent E4448A
Spectrum Analyzer

V_{dd}

RF probing

Bias-Tee

50 Ω

RF probing
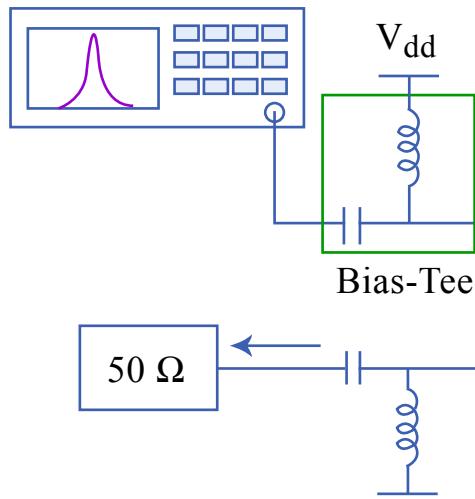
Open-collector buffer

S+

G

S-

CSWO core

L

Q   Q

L

2.1 mm
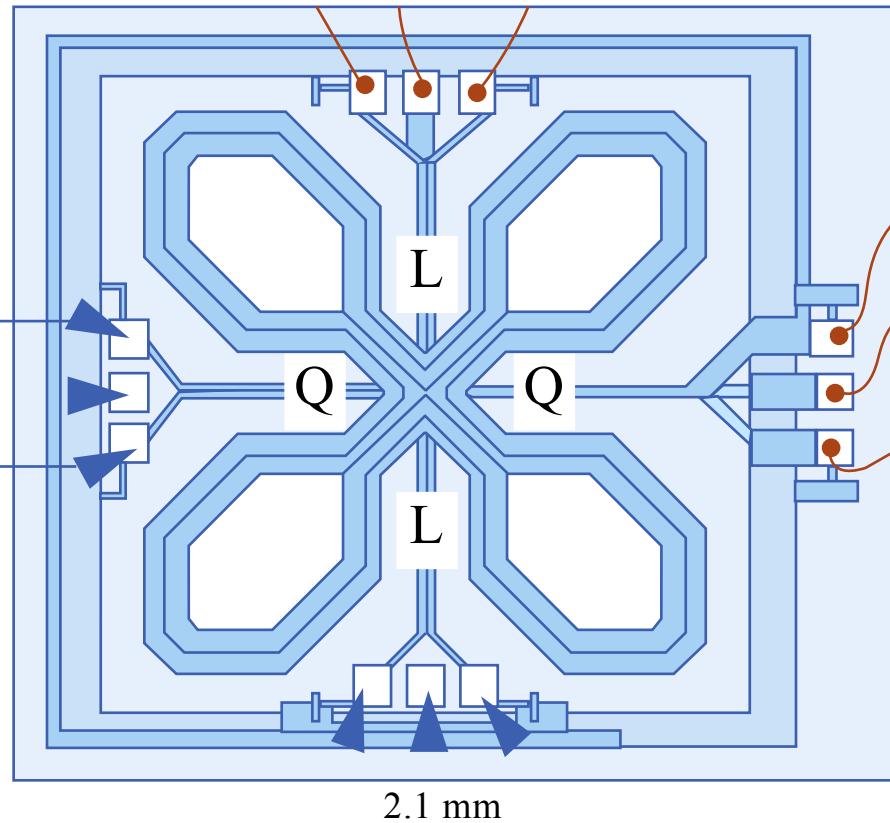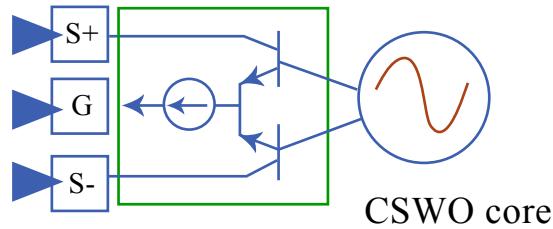
Mixers

Mixer Design for Wireless Systems
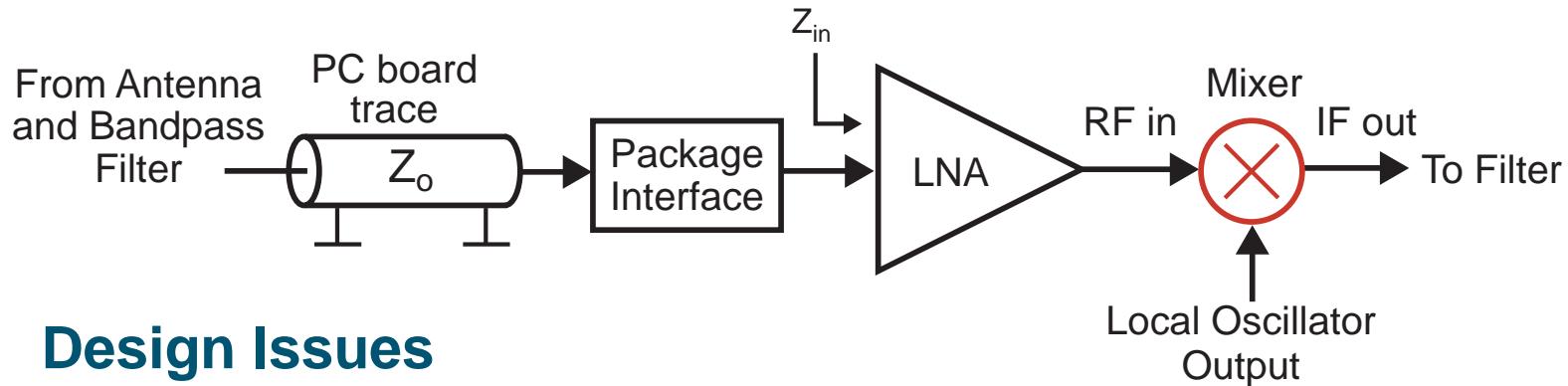

- **Design Issues**
  - **Noise Figure – impacts receiver sensitivity**
  - **Linearity (IIP3) – impacts receiver blocking performance**
  - **Conversion gain – lowers noise impact of following stages**
  - **Power match – want max voltage gain rather than power match for integrated designs**
  - **Power – want low power dissipation**
  - **Isolation – want to minimize interaction between the RF, IF, and LO ports**
  - **Sensitivity to process/temp variations – need to make it manufacturable in high volume**

Ideal Mixer Behavior
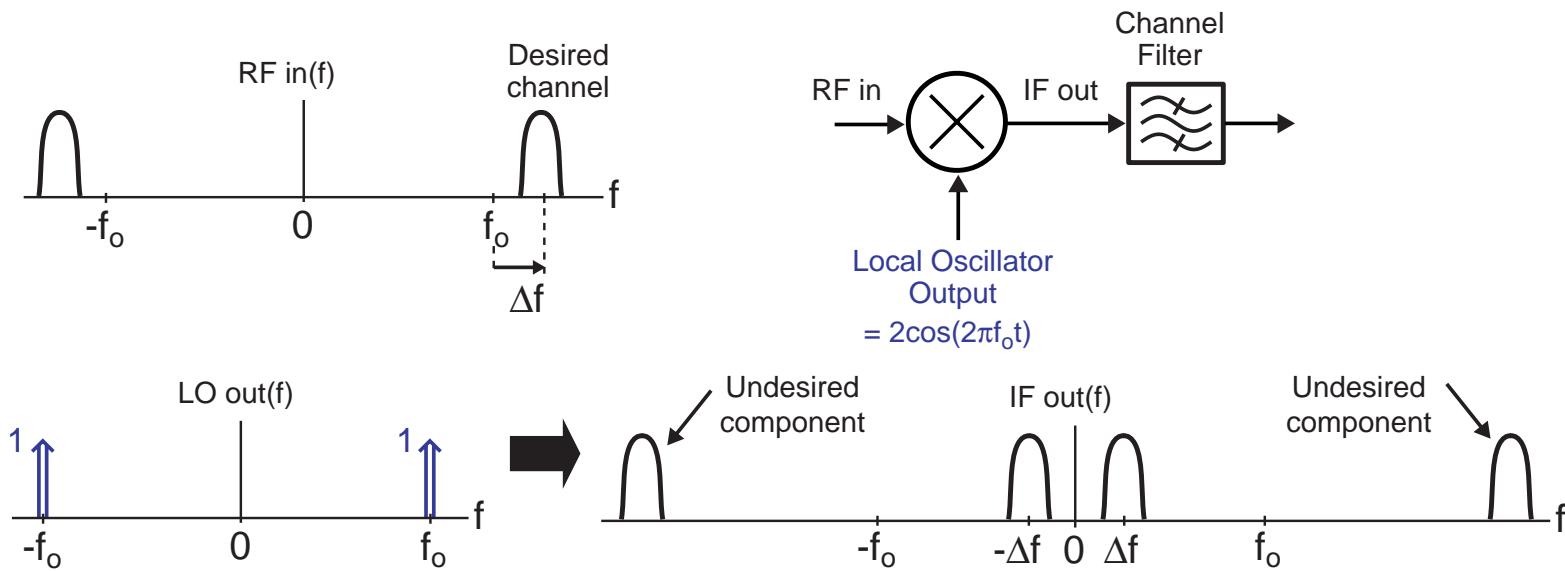
- **RF spectrum converted to a lower IF center frequency**
  - **IF stands for intermediate frequency**
    - If IF frequency is nonzero – heterodyne or low IF receiver
    - If IF frequency is zero – homodyne receiver
- **Use a filter at the IF output to remove undesired high frequency components**

The Issue of Image Aliasing
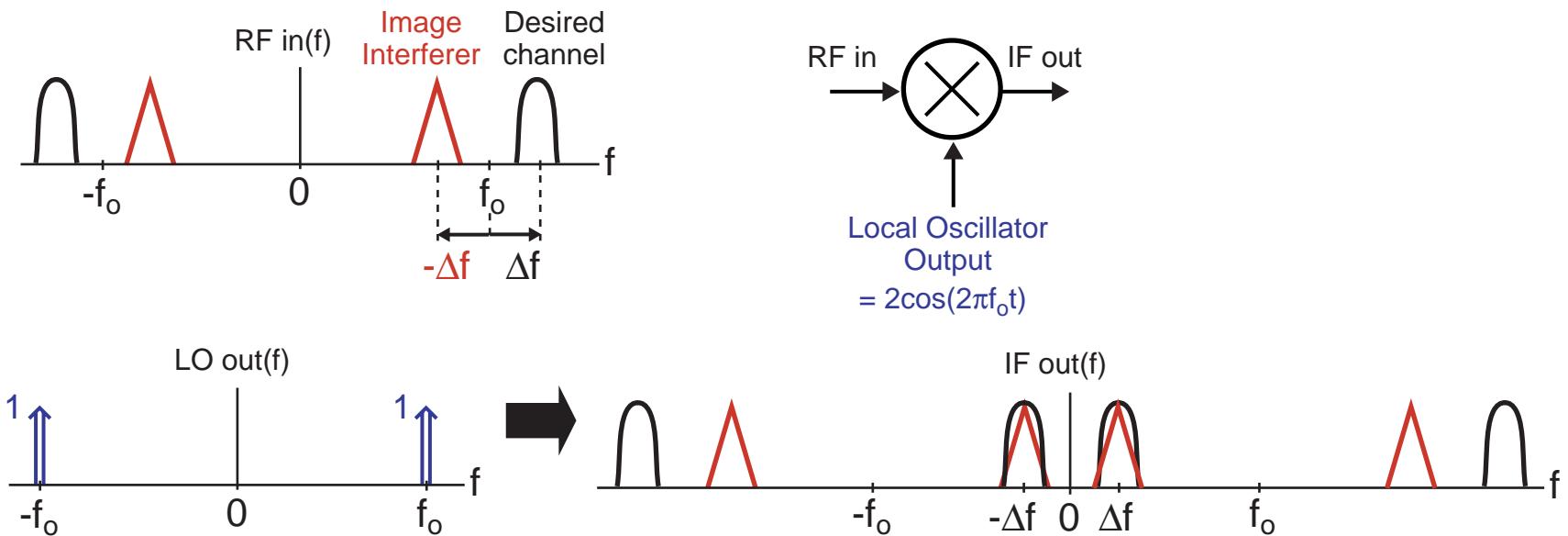
- **When the IF frequency is nonzero, there is an image band for a given desired channel band**
  - **Frequency content in image band will combine with that of the desired channel at the IF output**
  - **The impact of the image interference cannot be removed through filtering at the IF output!**

LO Feedthrough
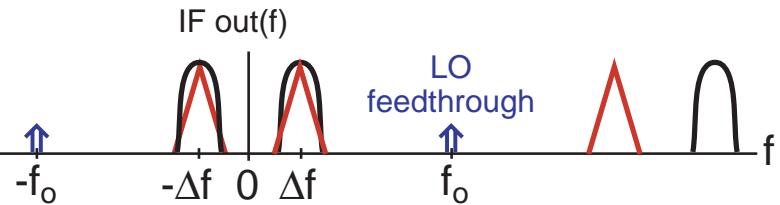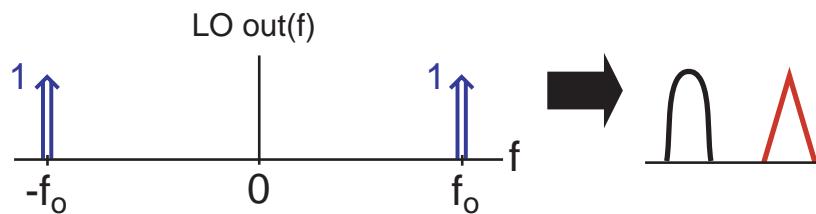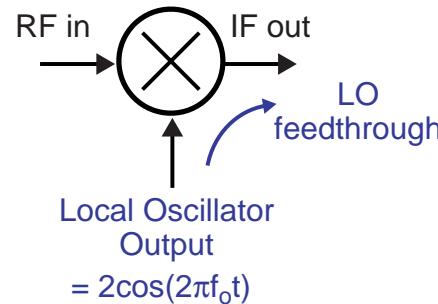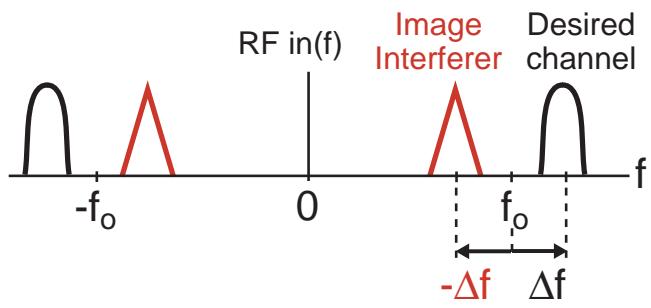
- **LO feedthrough will occur from the LO port to IF output port due to parasitic capacitance, power supply coupling, etc.**
  - **Often significant since LO output much higher than RF signal**
    - If large, can potentially desensitize the receiver due to the extra dynamic range consumed at the IF output
    - If small, can generally be removed by filter at IF output

Reverse LO Feedthrough
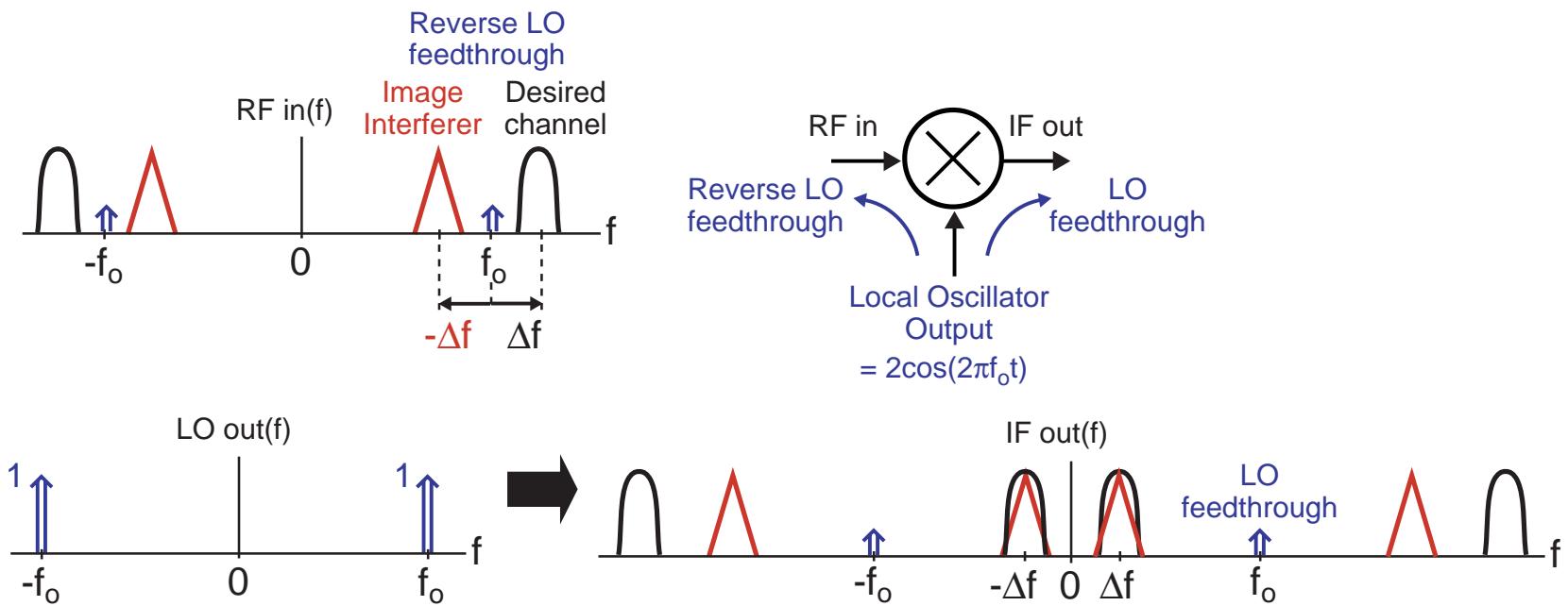
- **Reverse LO feedthrough will occur from the LO port to RF input port due to parasitic capacitance, etc.**
  - **If large, and LNA doesn't provide adequate isolation, then LO energy can leak out of antenna and violate emission standards for radio**
  - **Must insure that isolate to antenna is adequate**

Self-Mixing of Reverse LO Feedthrough
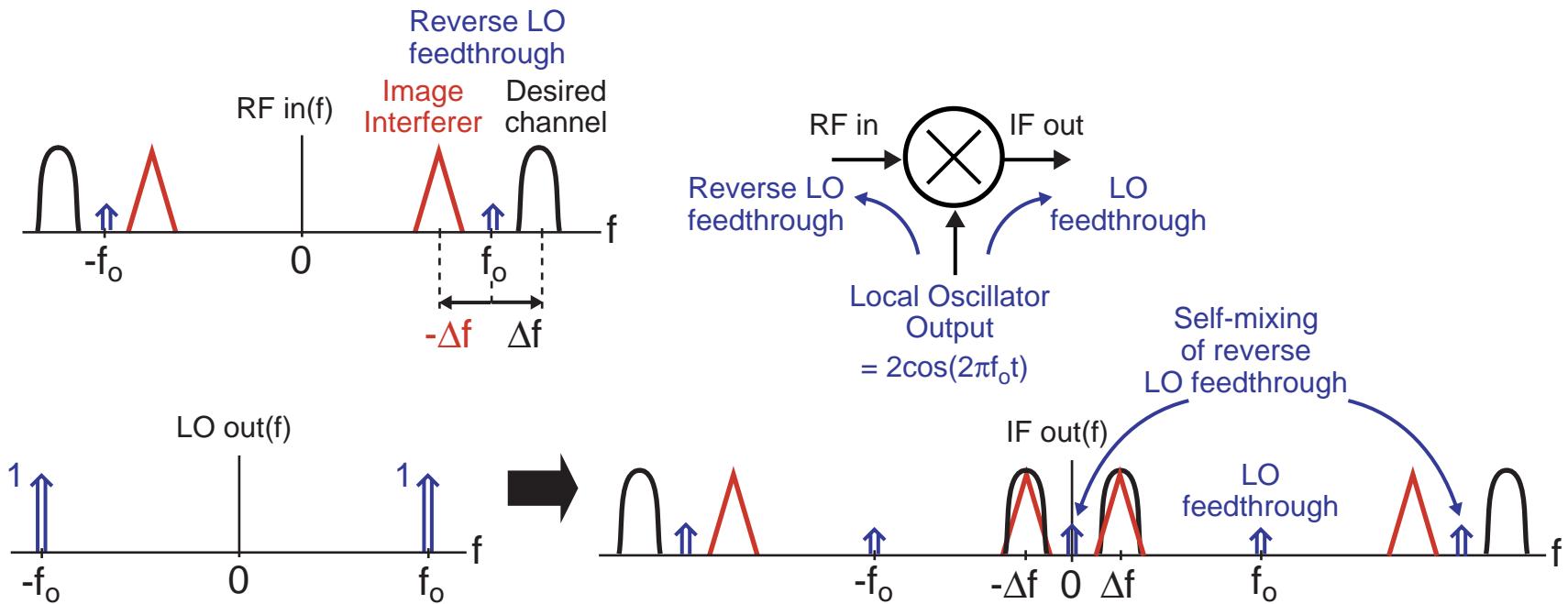
- **LO component in the RF input can pass back through the mixer and be modulated by the LO signal**
  - **DC and $2f_o$ component created at IF output**
  - **Of no consequence for a heterodyne system, but can cause problems for homodyne systems (i.e., zero IF)**

# *Removal of Image Interference – Solution 1*
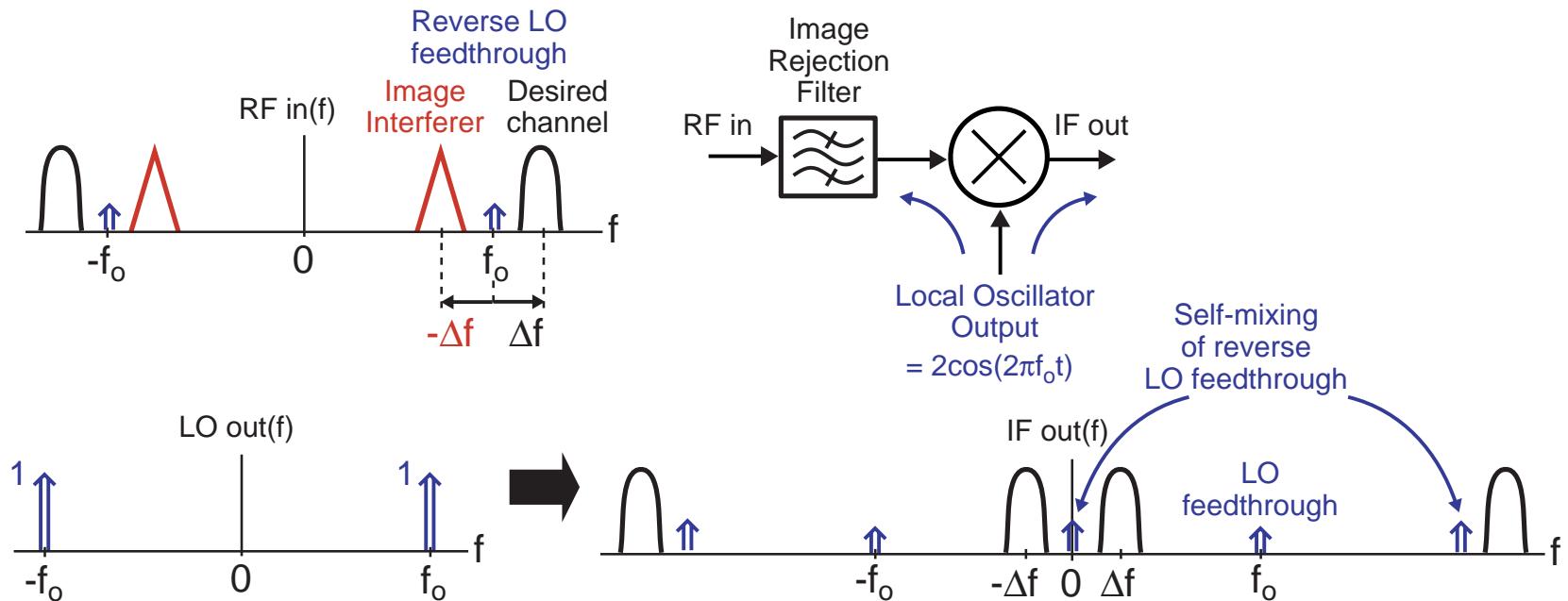
- **An image reject filter can be used *before* the mixer to prevent the image content from aliasing into the desired channel at the IF output**

- **Issue – must have a high IF frequency**
  - **Filter bandwidth must be large enough to pass all channels**
  - **Filter Q cannot be arbitrarily large (low IF requires high Q)**

# *Removal of Image Interference – Solution 2*
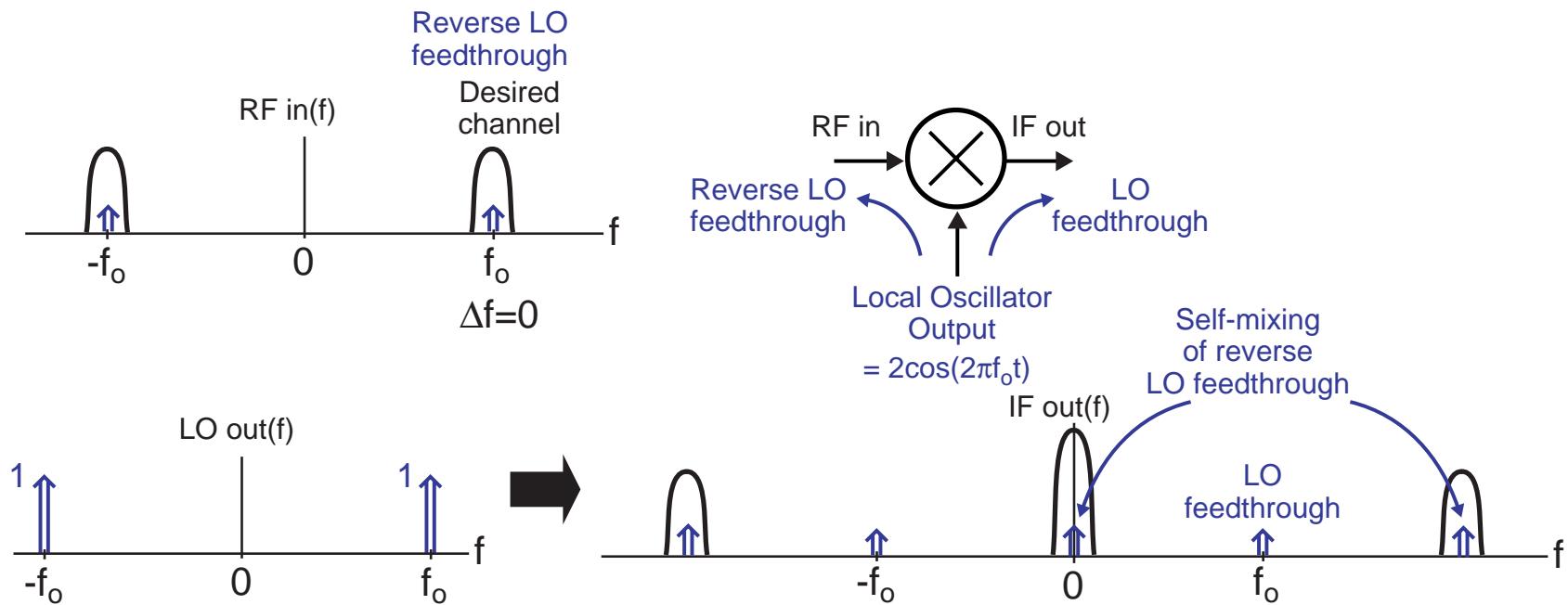
- **Mix directly down to baseband (i.e., homodyne approach)**
  - **With an IF frequency of zero, there is no image band**
- **Issues – many!**
  - **DC term of LO feedthrough can corrupt signal if time-varying**
  - **DC offsets can swamp out dynamic range at IF output**
  - **1/f noise, back radiation through antenna**

# *Removal of Image Interference – Solution 3, Image Reject Mixer*
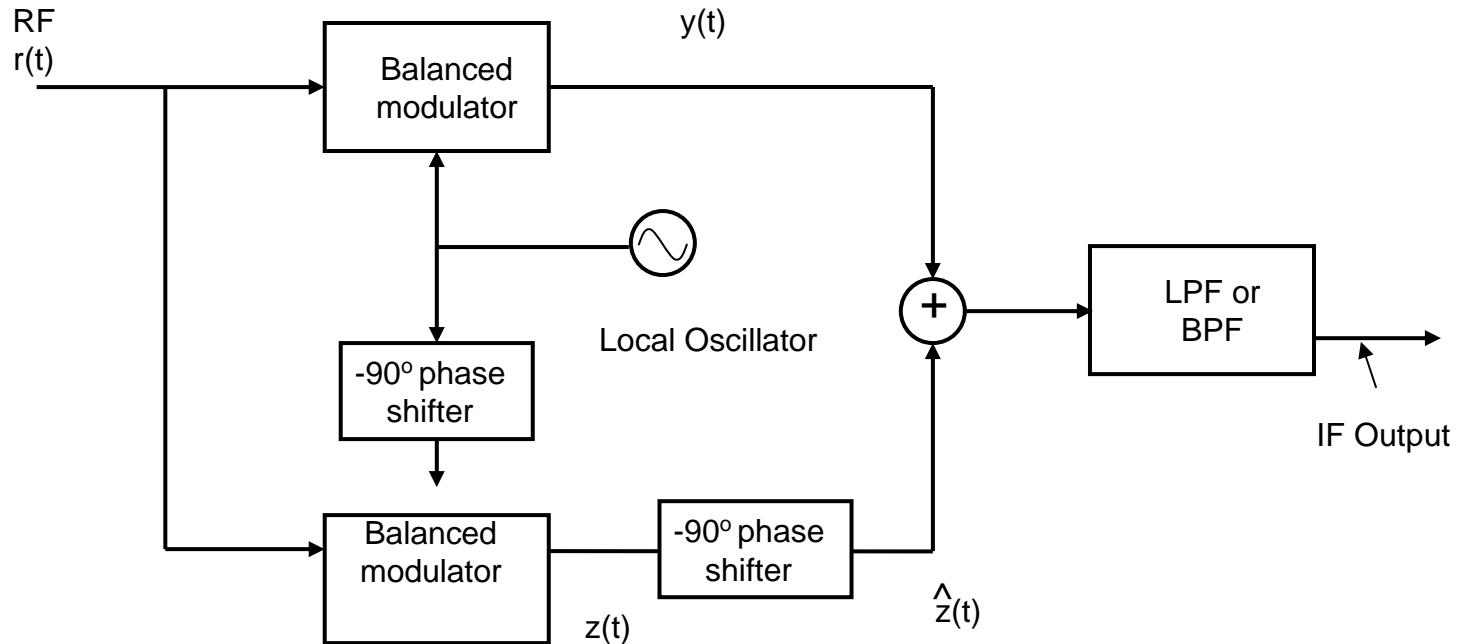
- **Image rejected by similar method to SSB generation**
- **Image rejection limited by amplitude and phase matching of RF and LO paths. 40 dB image suppression is typical**
- **RF filter can reduce the image further if necessary, otherwise the RF image reject filter can be omitted.**

Frequency Domain View of Image Reject Mixer
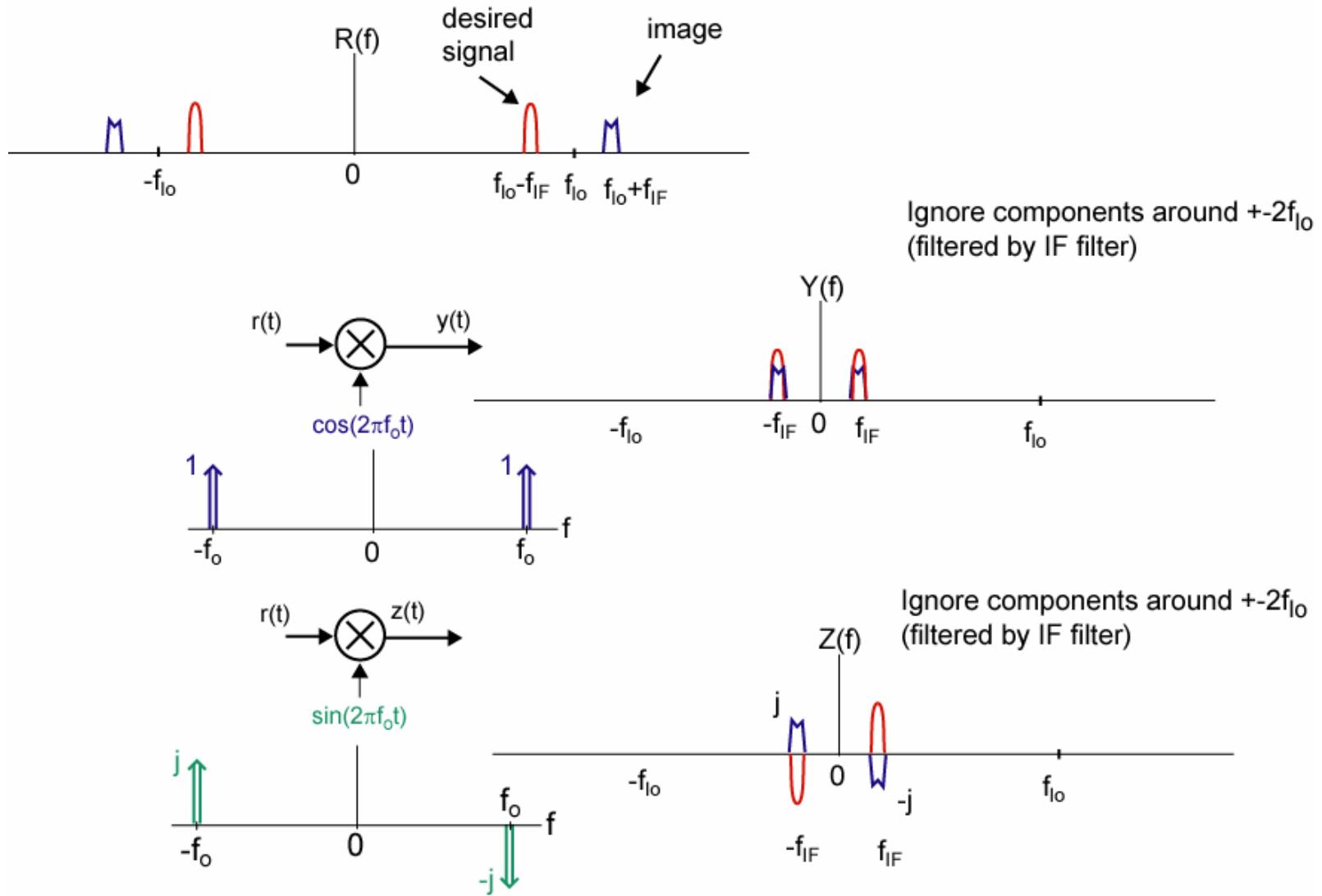
Frequency Domain View of Image Reject Mixer, Cnt'd

Ignore components around $+-2f_{lo}$
(filtered by IF filter)
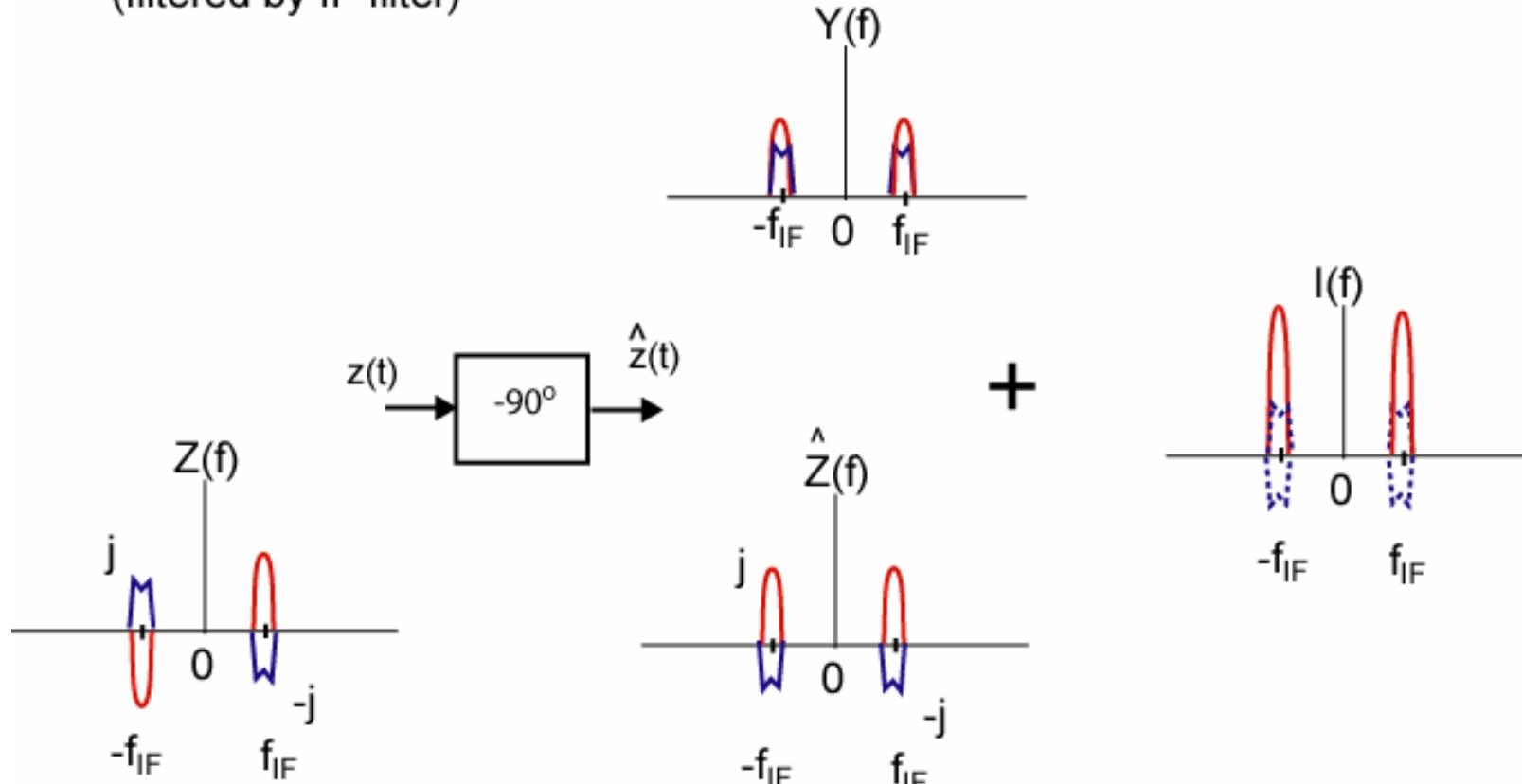
- **It can be shown that image is rejected regardless of the RF input phase**