1-GHz and 2.8-GHz CMOS Injection-locked Ring Oscillator Prescalers

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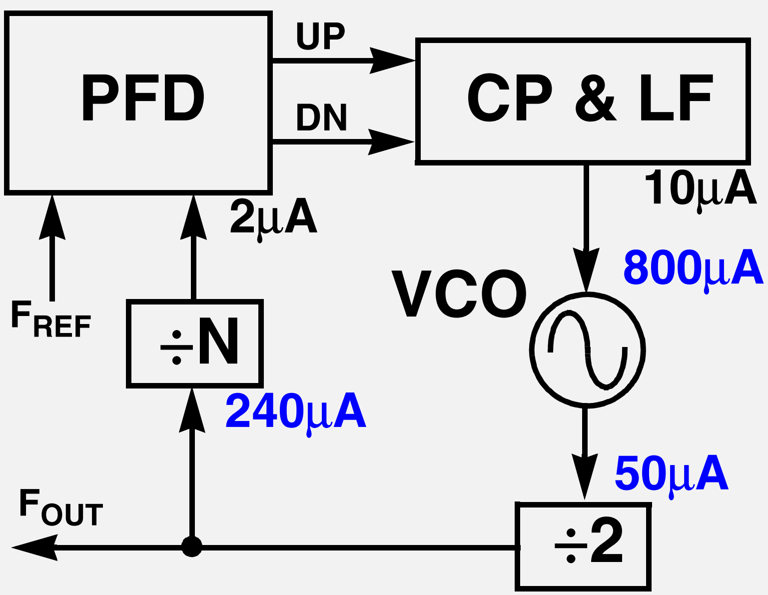
Outline

- ***Introduction***
- Injection Locking Theory
- Circuit Implementation
- Measured Results
- Conclusion

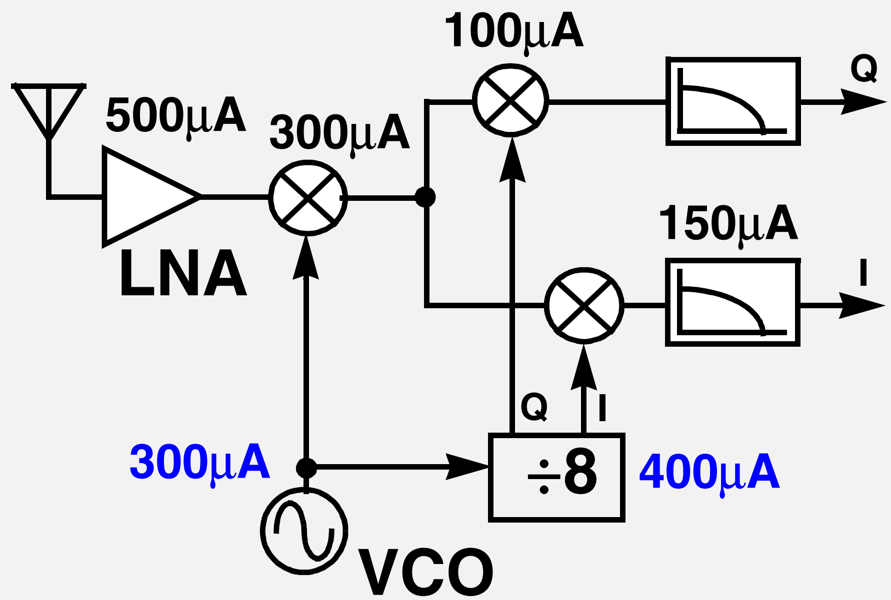
Goals

- **Understand the Injection-locking mechanism**
- **Grasp the limitations of Injection-locked Frequency Dividers**
- **Design Injection-locked Frequency Divider using a Ring Oscillator**

Motivation: Low-power Frequency Synthesis



320 MHz CMOS PLL
[V.Kaenel'96]

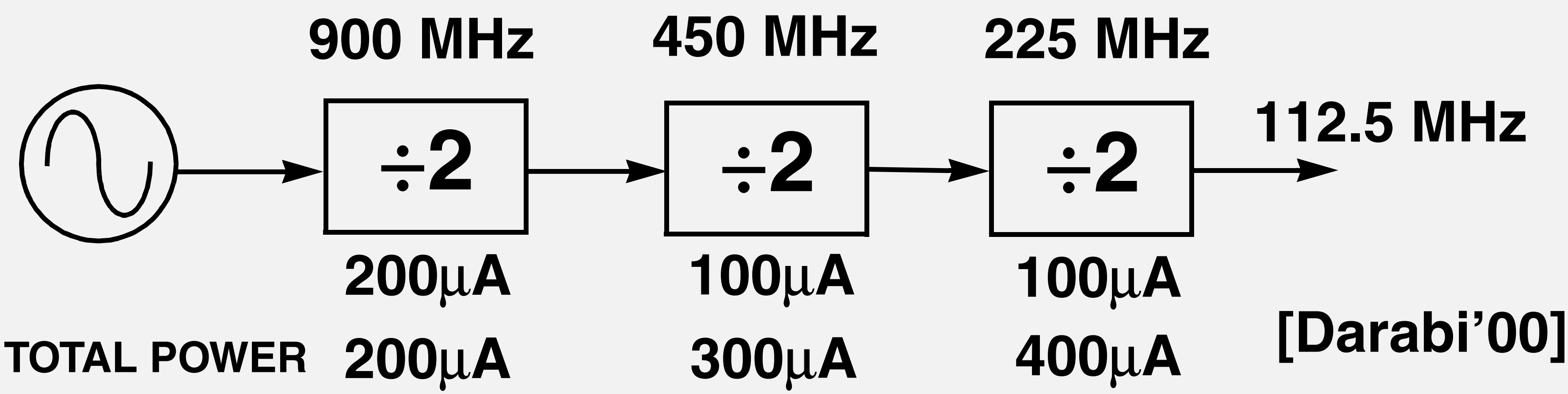


900 MHz CMOS RECEIVER
[Darabi'00]

- Frequency synthesizers are implemented using PLLs.
- Major sources of power dissipation are the VCO and Frequency Divider.

Frequency Divider Power Trade-off

POWER INCREASES WITH DIVISION RATIO



- We propose a technique in which power ***decreases*** with division ratio.

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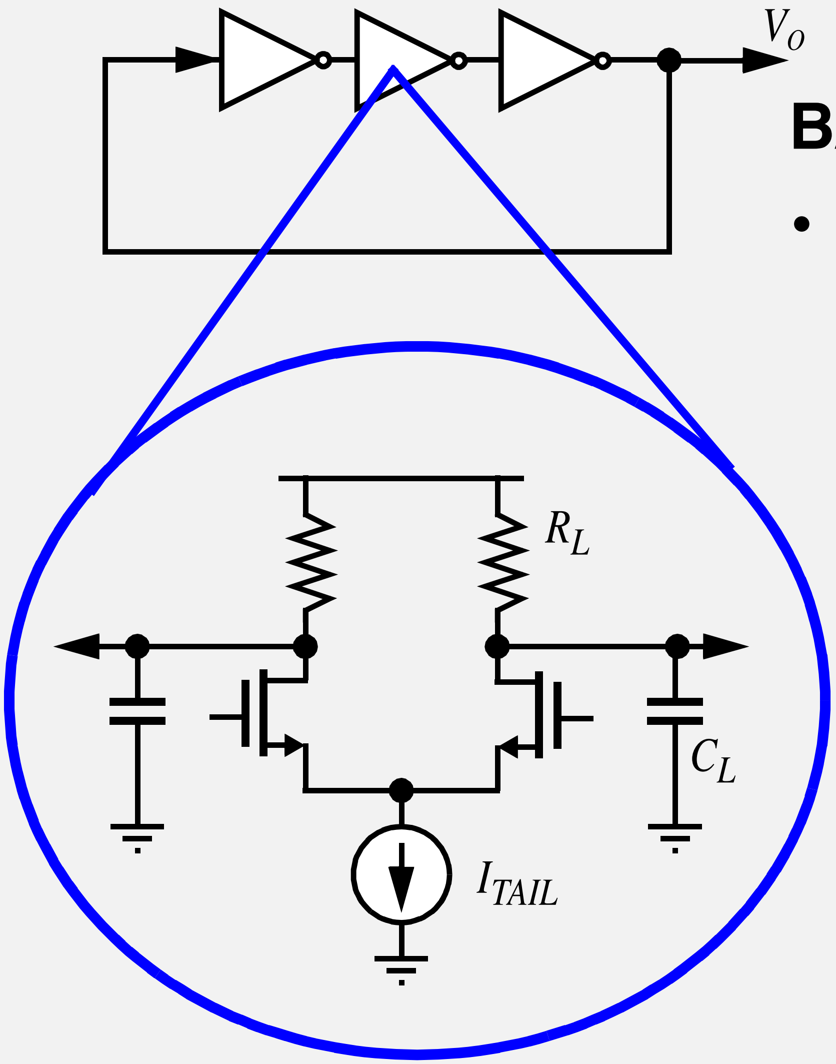
Ring Oscillator Model



- Neglect feedforward zero

BARKHAUSEN CRITERIA

- Necessary conditions for oscillation

GAIN CONDITION

$$|H(j\omega_O)| \geq 1$$

PHASE CONDITION

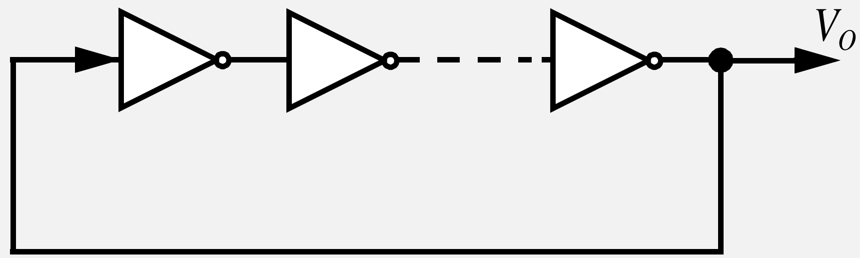
$$\angle H(j\omega_O) = 180^{\circ}$$

SMALL-SIGNAL MODEL

$$H_S(j\omega) = \frac{H_O}{1 + j\omega/\omega_P}$$

$$\omega_P = \frac{1}{R_L C_L}$$

Ring Oscillator Model (II)



GAIN CONDITION

$$H_O \geq \sqrt{1 + \tan\left(\frac{\pi}{n}\right)^2}$$

PHASE CONDITION

$$\omega_P = \frac{\omega_0}{\tan\left(\frac{\pi}{n}\right)}$$

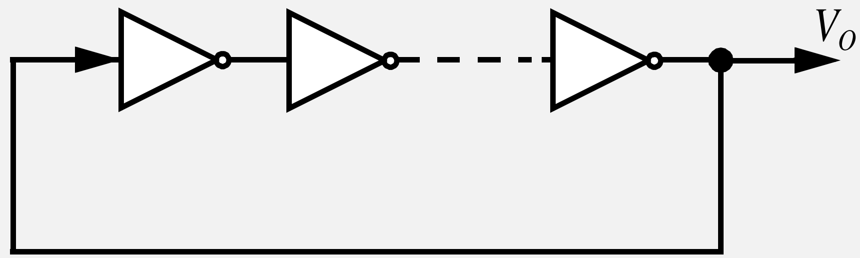
N-STAGE MODEL

$$H(j\omega) = \frac{H_O^n}{\left(1 + j\frac{\omega}{\omega_o}\tan\left(\frac{\pi}{n}\right)\right)^n}$$

$$n > 2$$

- ω_0 is free-running oscillator frequency.
- Each stage contributes π/n to the phase.

Ring Oscillator Model (III)



EXAMPLE

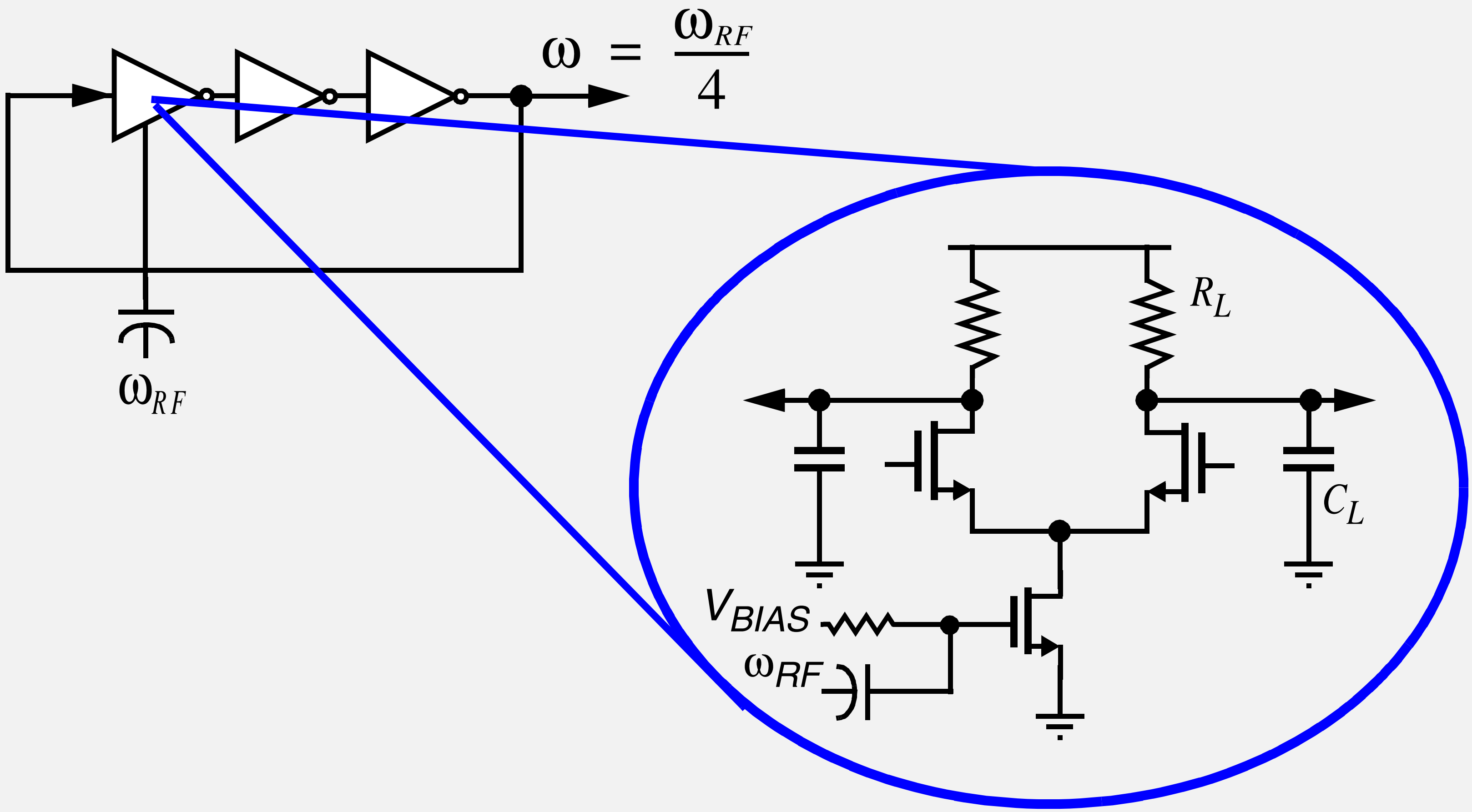
$$H(j\omega) = \frac{H_O^n}{\left(1 + j\frac{\omega}{\omega_o}\tan\left(\frac{\pi}{n}\right)\right)^n}$$

n	H_0	ω_p
3	2.00	0.58 ω_0
4	1.41	ω_0
5	1.24	1.38 ω_0

- DC gain H_0 decreases with number of stages.
- Poles ω_p coincide with ω_0 only for n=4.

Injection-locked Ring Oscillator

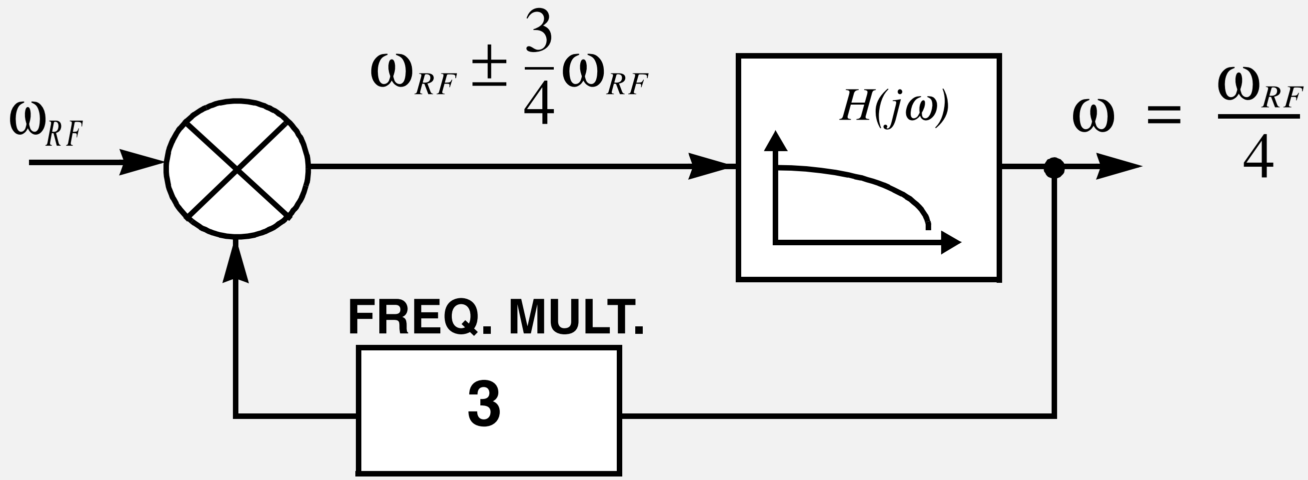
EXAMPLE: 3-stage, Divide by 4



- An oscillator can be injection-locked to a harmonic of the free-running oscillation frequency.

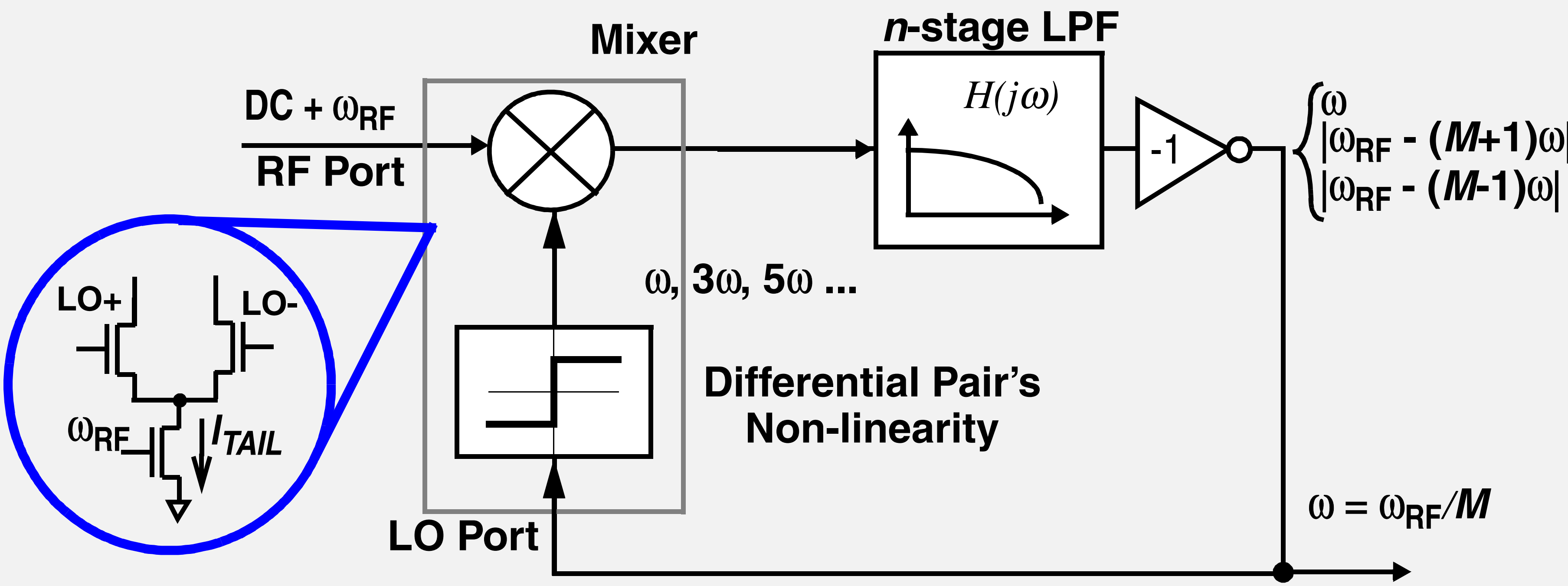
Regenerative Divider [Miller 1939]

EXAMPLE: Divide by 4



- Commonly used where the frequency of operation is very high, beyond what can be achieved with flip-flop based circuits.
- Frequency multiplier can represent non-linearities present in the circuit.
- Used a model similar to Miller's, since the locking mechanisms are identical.

Model for Injection-locked Frequency Divider



MIXER

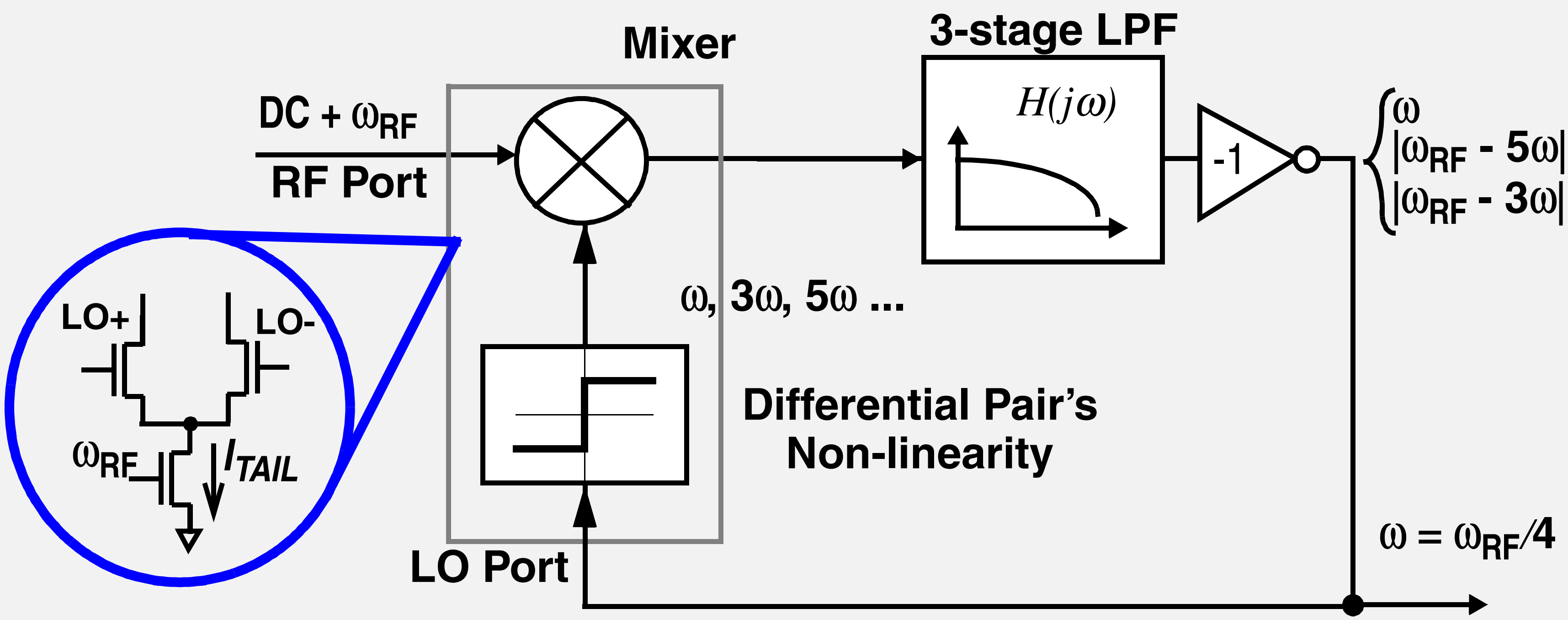
- Differential-pair single-balanced mixer
- Injected ω_{RF} into the tail device

FILTER

- Suppress products > ω
- V_O is sinusoidal (small n).

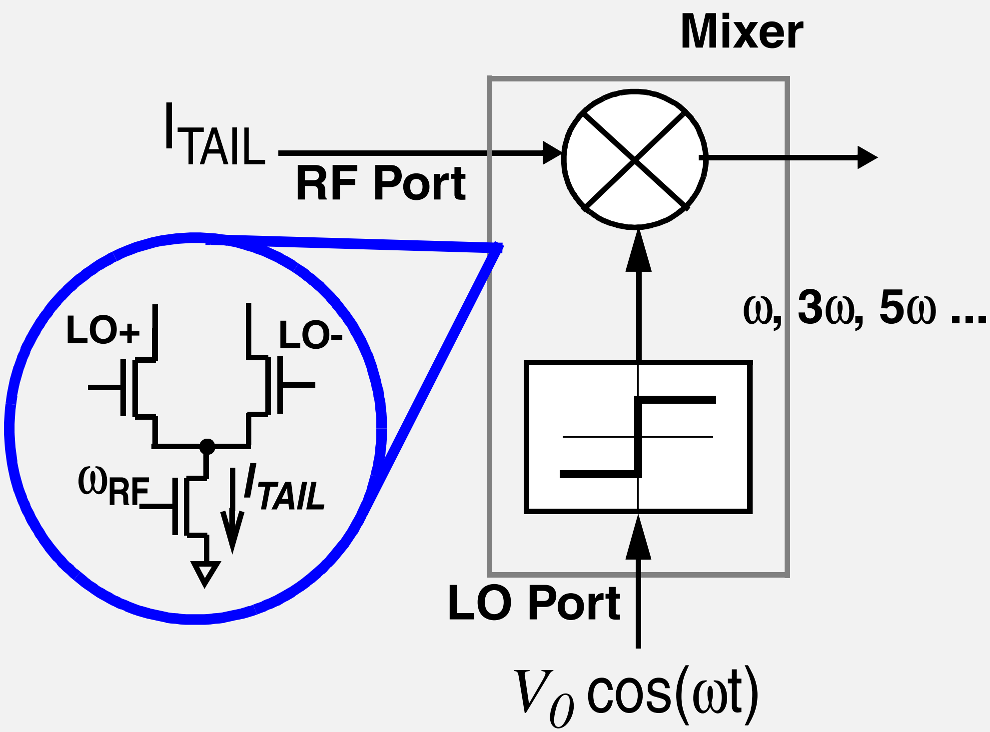
Model for Injection-locked Frequency Divider (II)

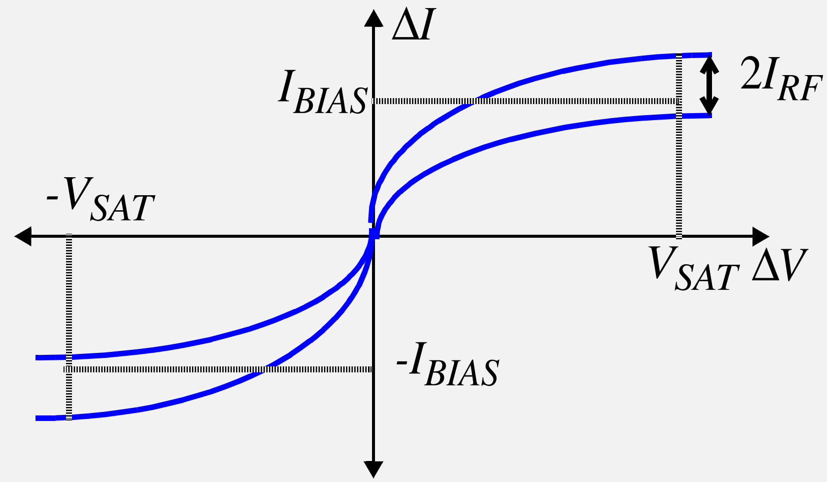
EXAMPLE: 3-stage, Divide by 4



- With no injection, $\omega = \omega_0$.

Mixer





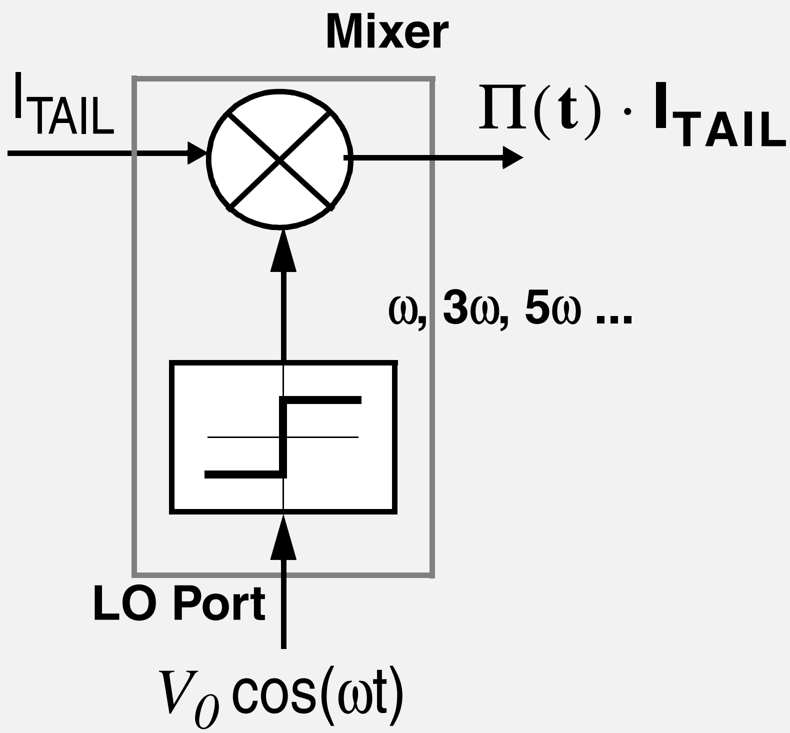
$$I_{TAIL} = I_{RF} \cos(\omega_{RF} t + \alpha) + I_{BIAS}$$

$$V_{SAT} = \sqrt{\frac{(W/L)_{TAIL}}{(W/L)_{DIFF}}} \cdot V_{ODT}$$

- The differential-pair is non-linear with odd symmetry.
- Non-linearity produces odd harmonics at 3ω, 5ω, etc.
- I_{TAIL} is modulated by ω and its harmonics.

DEFINE SWING RATIO

$\rho_s = V_0/V_{SAT}$ **>> 1 (Square Wave)**



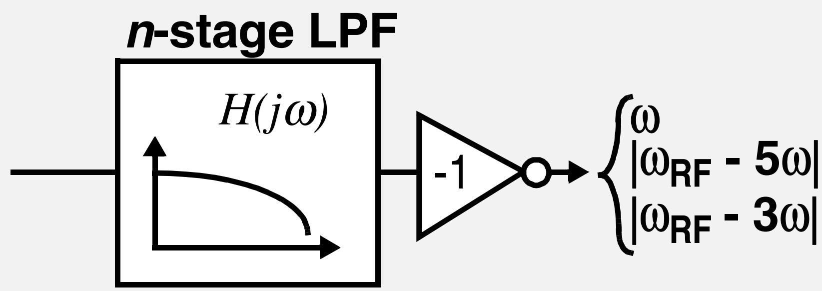
Fourier Coefficients of Mixing Function Π(t)

$$C_k = \begin{cases} \frac{1}{k\pi} \cdot (-1)^{(k-1)/2} & odd\ k \\ 0 & otherwise \end{cases}$$

Filter

Use Ring Oscillator Model

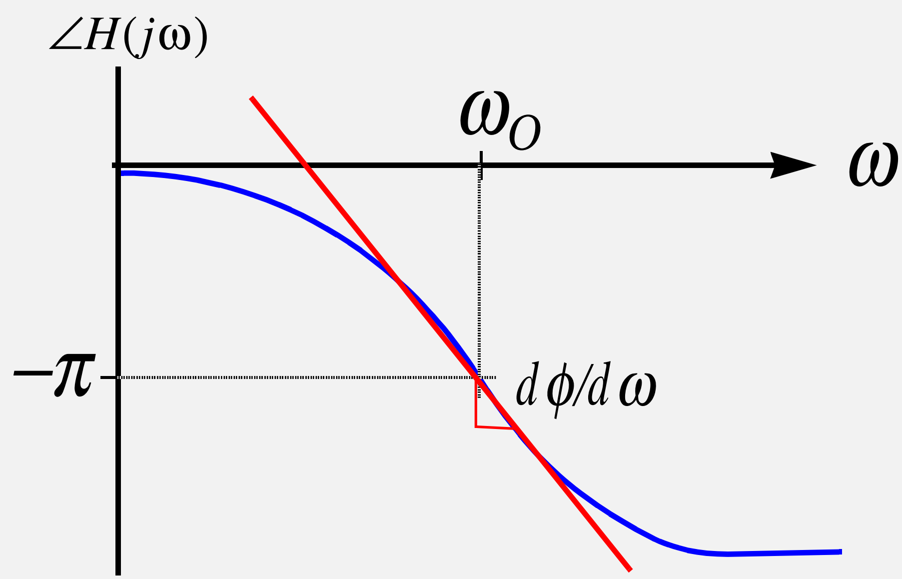
$$H(j\omega) = \frac{H_O^n}{\left(1 + j\frac{\omega}{\omega_o}\tan\left(\frac{\pi}{n}\right)\right)^n}$$



Linearize Phase of *H(jω)*

$$-\angle H(j\omega) \cong \pi + \frac{n\sin\left(\frac{2\pi}{n}\right)}{2} \cdot \frac{\Delta\omega}{\omega_0}$$

$$\Delta\omega = \omega - \omega_O$$



Describing Function Analysis

WRITE PHASE EXPRESSION AROUND THE LOOP

$$\underbrace{\operatorname{atan}\left(\frac{\eta_i(C_{M-1} - C_{M+1})\sin\alpha}{C_1 + \eta_i(C_{M-1} + C_{M+1})\cos\alpha}\right)}_{\text{MIXER}} = \underbrace{-\angle Hj\omega - \pi}_{\text{FILTER}} \qquad \underbrace{\eta_i = \frac{I_{RF}}{2I_{BIAS}}}_{\text{INJECTION EFFICIENCY}}$$

FIND SOLUTION FOR $\alpha \in (-\pi, \pi]$.

- If V_O is large, then the injection locking dynamics are determined by the phase relationship around the loop (phase-limited) and therefore we can ignore the amplitude expression.

Locking Range of Injection-locked Ring Oscillator

$$LR \cong \frac{4}{n \sin\left(\frac{2\pi}{n}\right)} \operatorname{atan}\left(\frac{k_0}{\sqrt{1 - k_1^{\,2}}}\right)$$

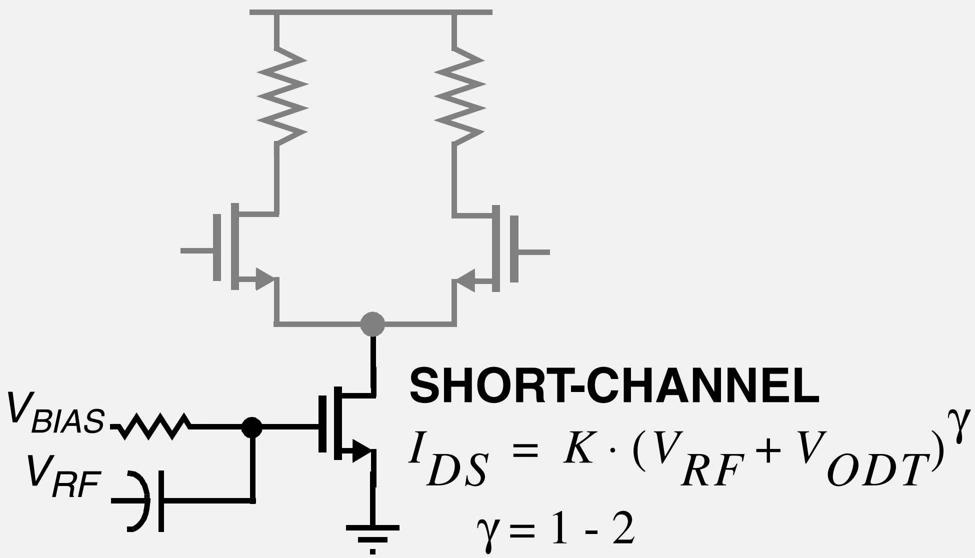
WHERE

$$k_0 = \eta_i \left| \frac{C_{M-1} - C_{M+1}}{C_1} \right| \qquad k_1 = \eta_i \left| \frac{C_{M-1} + C_{M+1}}{C_1} \right|$$

- Function of injection efficiency η_i, and the magnitude of the Fourier coefficients C_{M-1} and C_{M+1}.
- For small values of injected signal the locking range increases linearly with the injected signal strength.

Limited Injection Efficiency and Parasitics

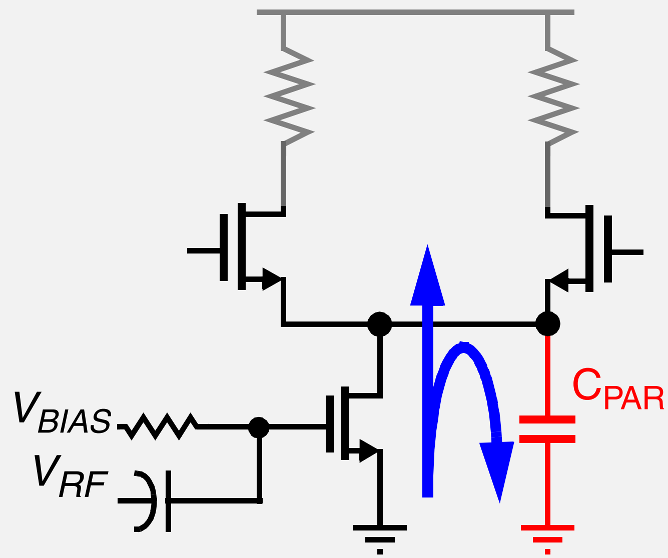
INJECTOR NON-IDEALITIES



$$\eta_i = \frac{V_{RF}}{2V_{ODT}} \cdot \gamma$$

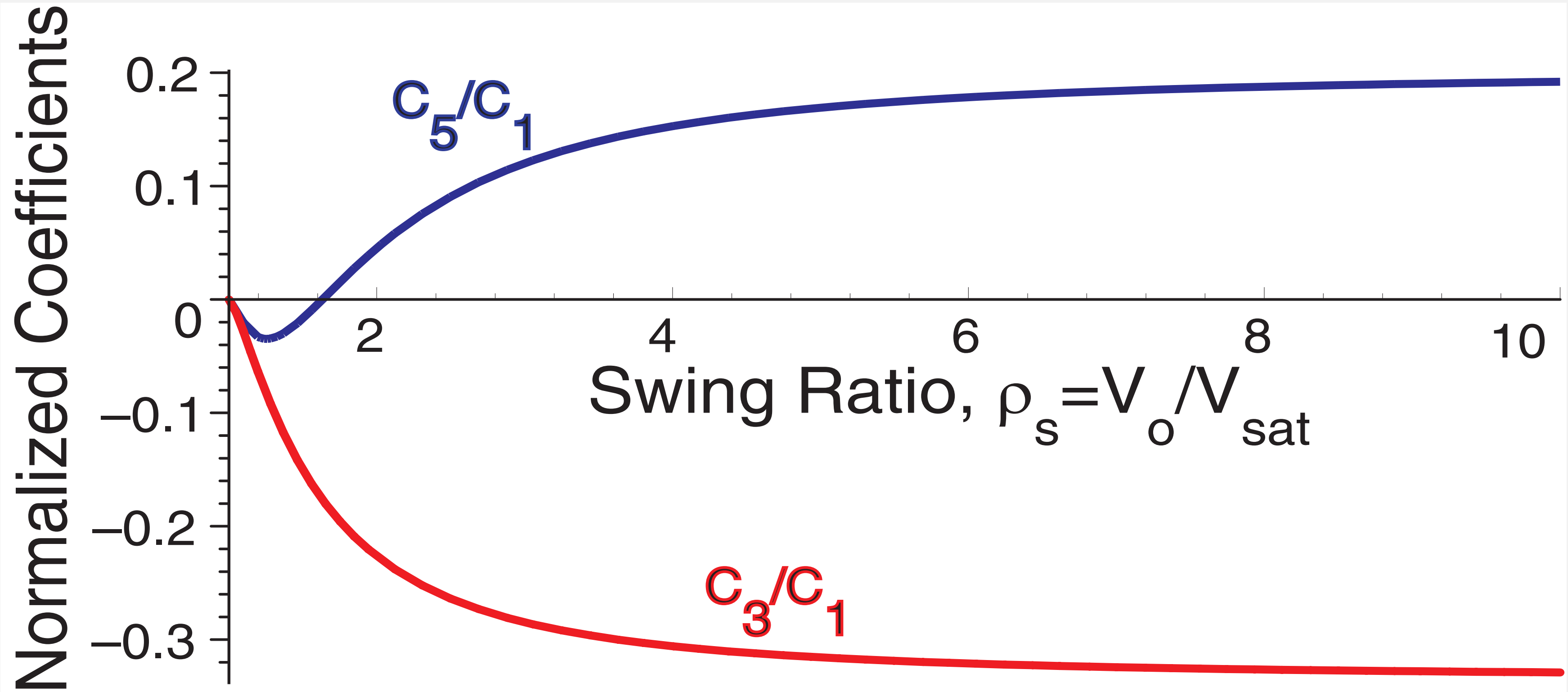
- Limited injection efficiency due to short-channel effects and tail device non-linearity.

TAIL PARASITICS



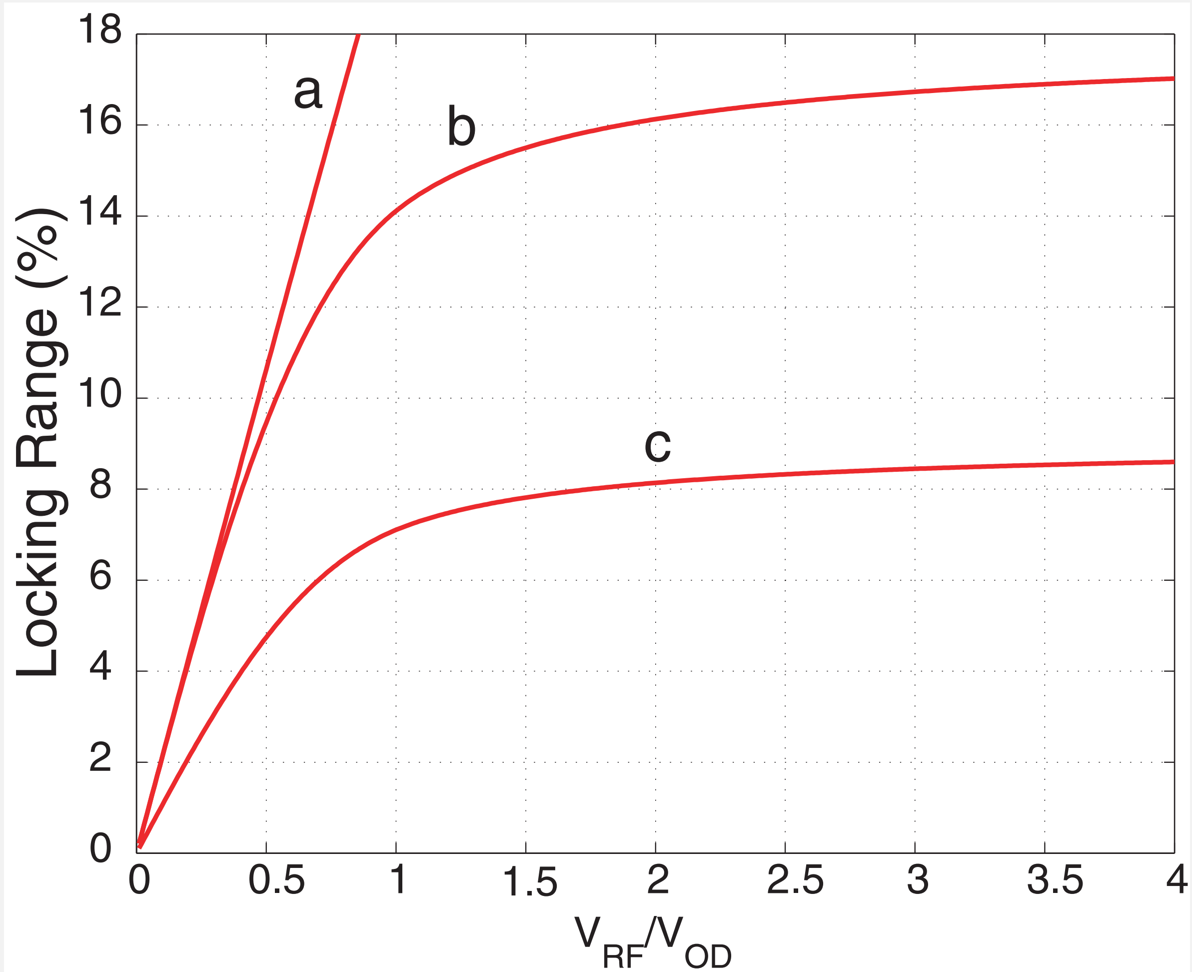
- Shunt path for I_{RF} reducing the injection efficiency at high frequencies.

Limited Mixer Gain



- The assumption that the mixer's switching function is a square wave is very accurate if the swing ratio $\rho_s >> 1$.
- As ρ_s gets smaller, the normalized coefficients C_k/C_1 are significantly smaller, thus degrading the locking range.

Example: 5-stage, Modulo-8 Ring Oscillator



(a)Ideal (phase-limited) case

(b)Compression due to Injector non-linearity (square-law device)

(c)Effects of Injector non-linearity and tail parasitics (50% loss)

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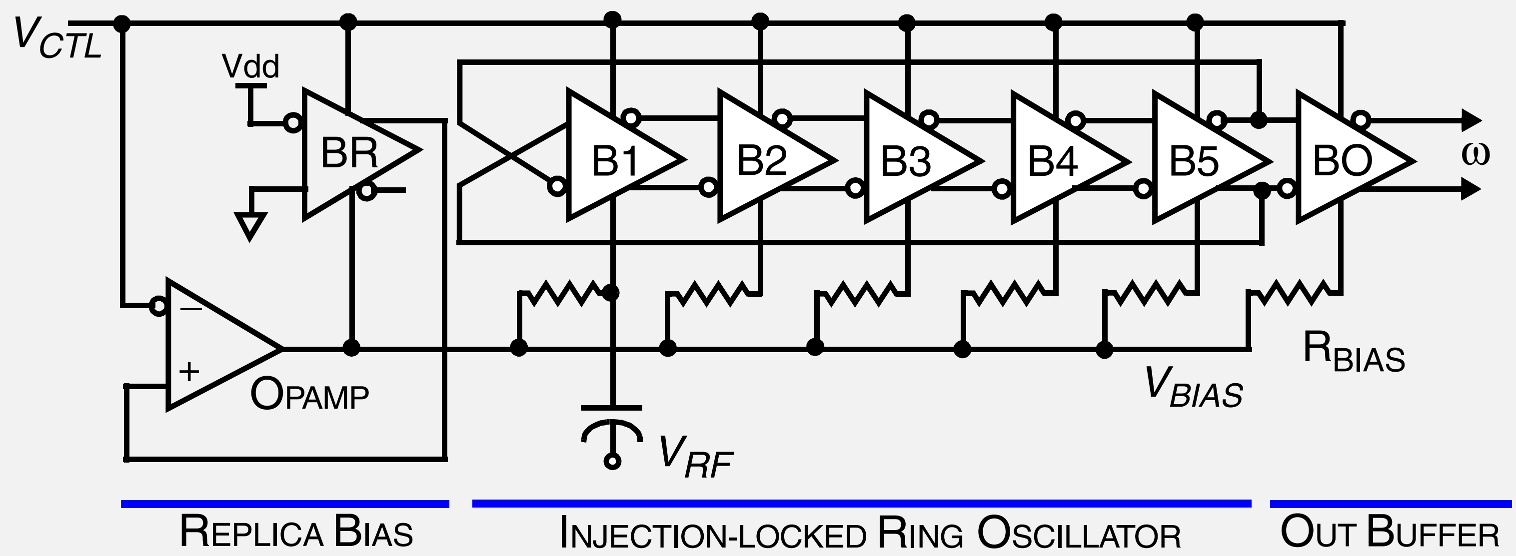
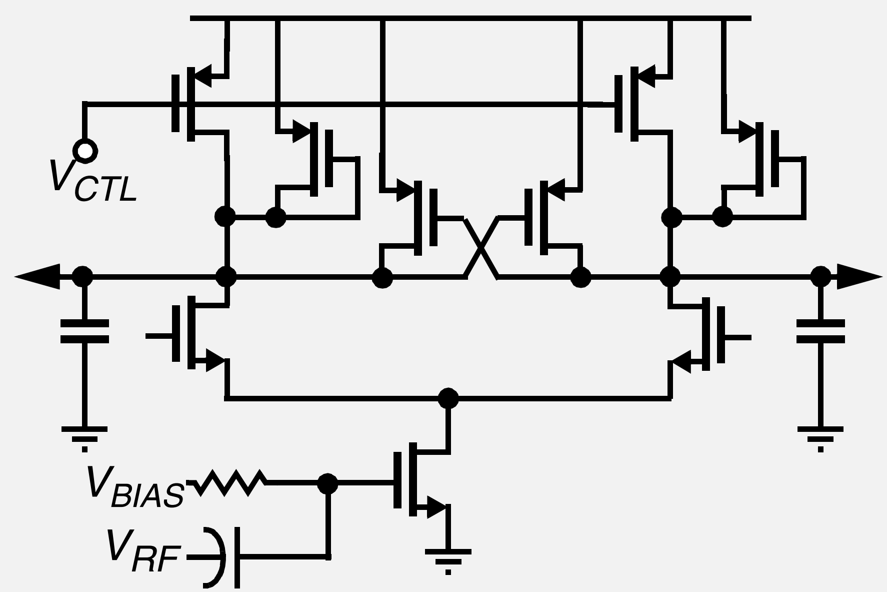
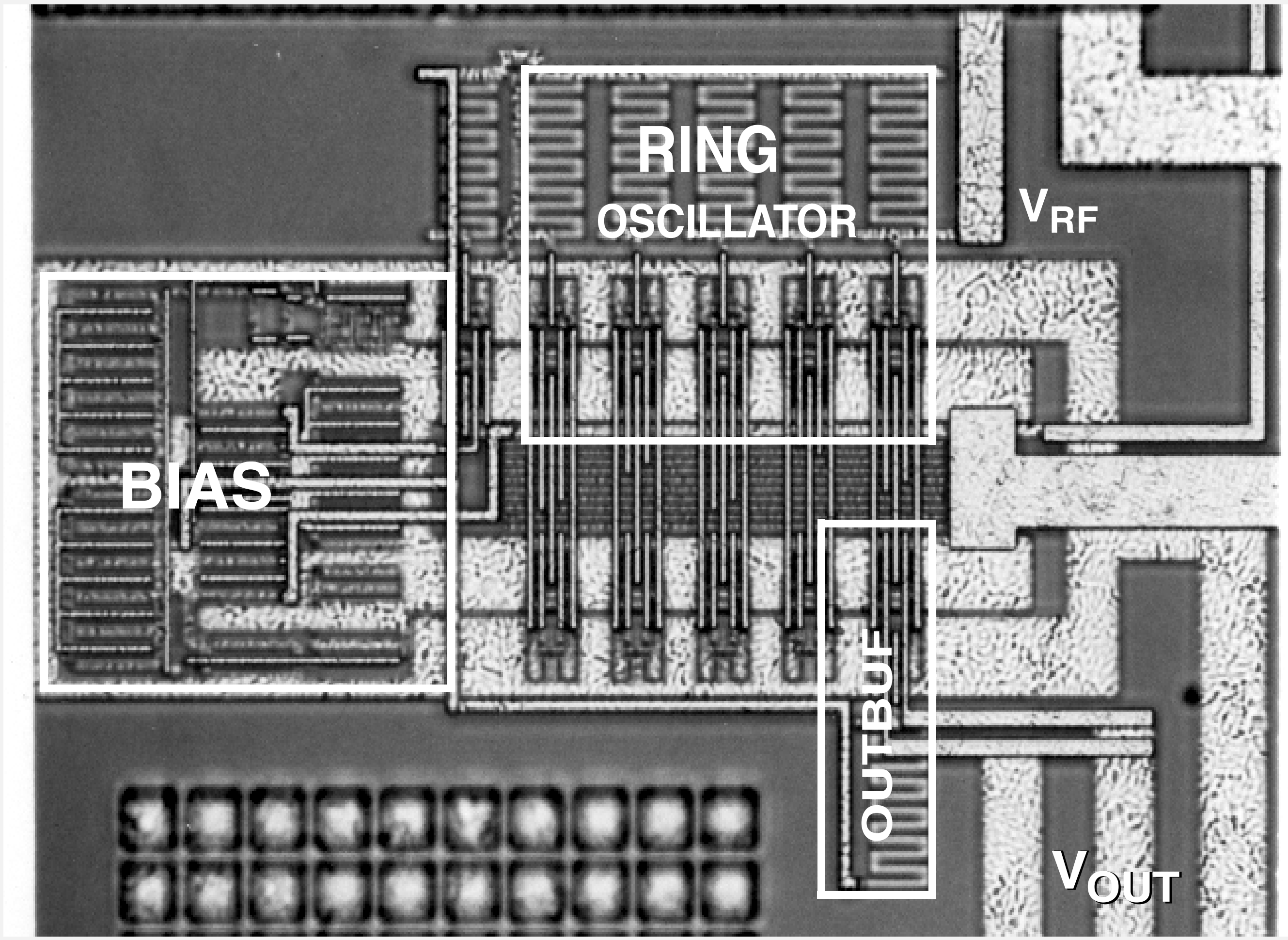
5-stage Injection-locked Ring Oscillator Frequency Divider



- Used modified cross-coupled symmetric load buffers.
- RF signal injected at the tail of the first buffer (single-balanced mixer).
- The buffer stages behave as the $H(j\omega)$ filter.



Die Micrograph: 5-stage Ring Oscillator Divider



- Fabricated 3 and 5-stage ring oscillators.
- 0.24-μm CMOS
- 0.012 mm^2 of area

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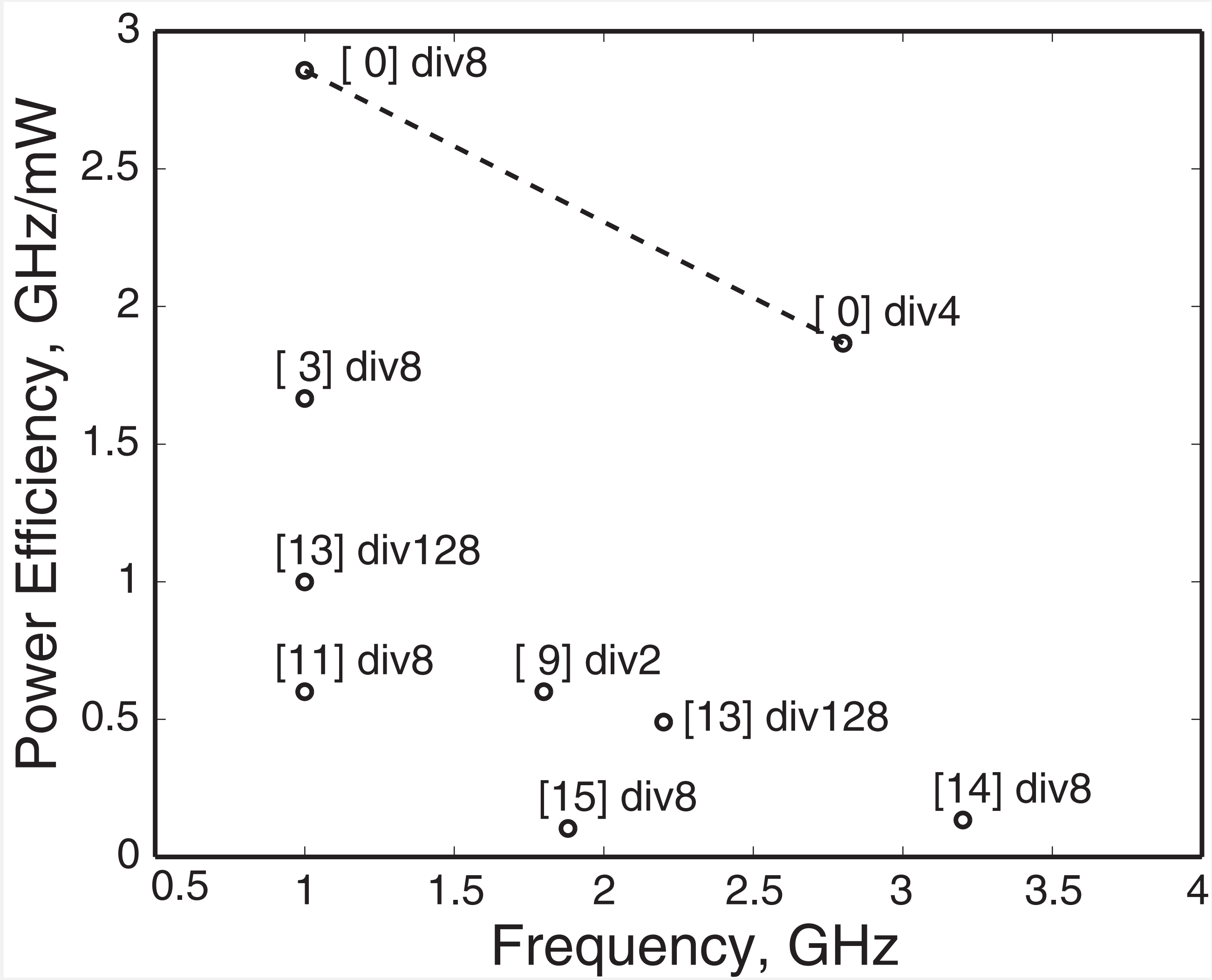
Results

	5-stage ILFD	*3-stage ILFD*
Injected Frequency	1.0 GHz	2.8 GHz
Free-running Frequency	125 MHz	700 MHz
Phase Noise@100KHz	-110 dBc/Hz	-106 dBc/Hz
Input Locking Range		
Modulo-2	12.7 MHz (-3dBm)	125 MHz (-3dBm)
Modulo-4	32 MHz (-3dBm)	56 MHz (-5dBm)
Modulo-6	17 MHz (-3dBm)	no-lock
Modulo-8	20 MHz (-3dBm)	no-lock
Power dissipation		
Vdd	1.5 V	3.0 V
Icore	233 μA	331 μA
Ibias	108 μA	661 μA
Core power	350 μW	993 μW
Power efficiency	2.86 GHz/mW	2.82 GHz/mW

Power Efficiency of Injection-locked Ring Oscillator



- [0] 5-stage (div-8) = 2.86 GHz/mW @1GHz
- [0] 3-stage (div-4) = 2.82 GHz/mW @2.8GHz

What We Learned

LOCKING RANGE COMPARISON

	5-stage (div-8) @ 1 GHz	**3-stage (div-4) @ 2.8 GHz**
THEORY	9%	34%
SIMULATION	5%	17%
TEST	2%	2%

- Large tail device (W/L=10.2/1) caused loss of I_{RF}. Need to lower tail node parasitics to increase the injection efficiency.
  - Resonating tail with an inductor [*Wu, ISSCC'01*] is not practical at sub-GHz frequencies.
- Small swing ratio $(\rho_s \approx 3\text{–}4)$ caused reduction in mixer gain. Need to increase output swing and reduce V_{SAT}.

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Conclusion

- Described the injection locking mechanism and how it applies to CMOS ring oscillators.
- Showed the design of frequency dividers that can operate up to 2.8-GHz by exploiting injection locking in differential CMOS ring oscillators.
- Showed measured results for 1-GHz and 2.8-GHz injection-locked frequency dividers fabricated in a 0.24-μm CMOS technology.

Acknowledgments

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