

CMOS Injection-locked Ring Oscillator Frequency Dividers

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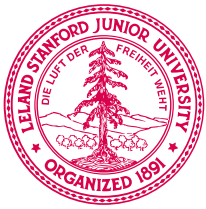
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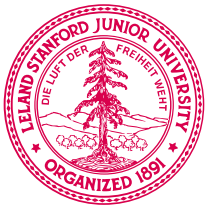
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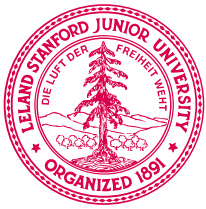
Outline

- **Goals**
- Ring Oscillator Overview
- Injection Locking Theory
- Circuit Implementation
- Measured Results
- Conclusion



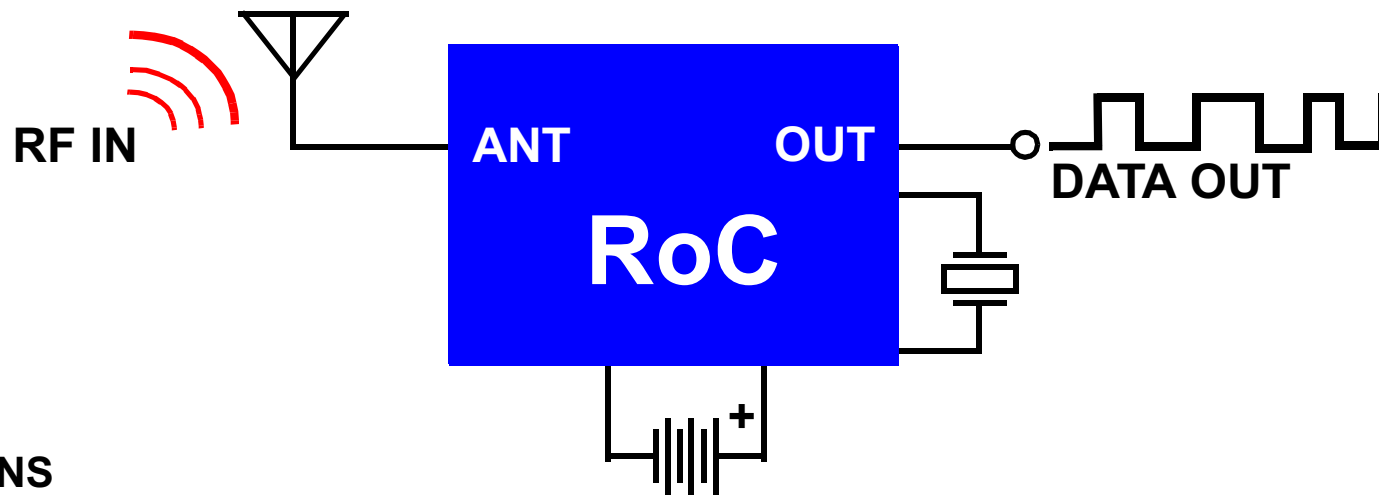
Goals

- Appreciate the trade-offs of low-power frequency synthesis
- Understand the operation of Ring Oscillators
- Understand the Injection-locking mechanism
- Grasp the limitations of Injection-locked Frequency Dividers
- Design Injection-locked Frequency Divider using a Ring



Motivation

A short-haul, low-power, radio-on-a-chip (RoC) that requires no external components can enable novel applications that are not economically feasible otherwise.



APPLICATIONS

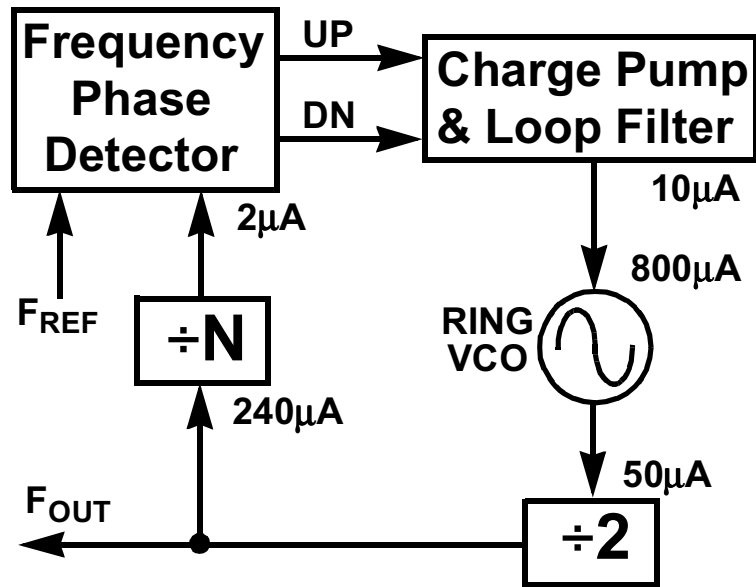
- Ambulatory health monitoring and biotelemetry
- Building and environmental monitoring
- Distribution and retail inventory management
- Wireless Internet access
- Home and factory automation

ISSUES

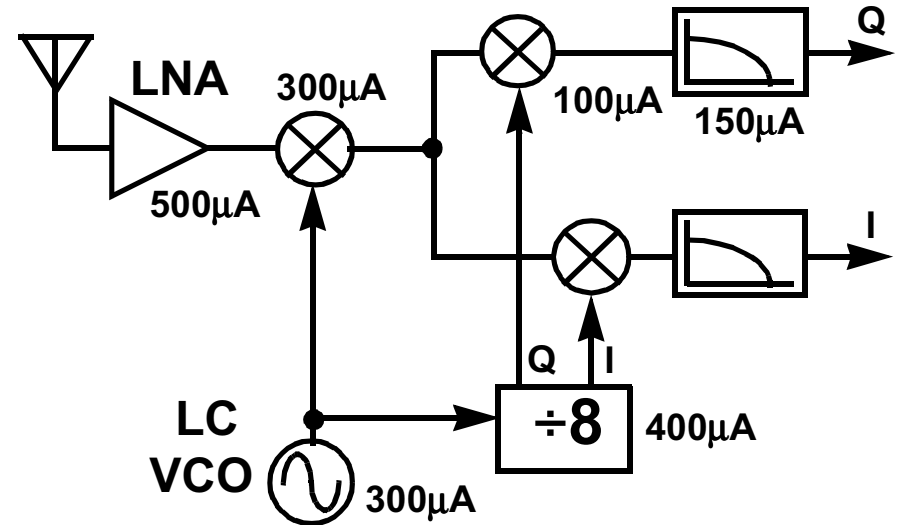
- A significant portion of the power budget is allocated to the generation of the RF local oscillator.
- Requires a low-power, completely integrated frequency synthesizer.



Low-power Frequency Synthesis

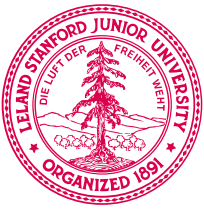


320 MHz CMOS PLL [V.Kaenel'96]

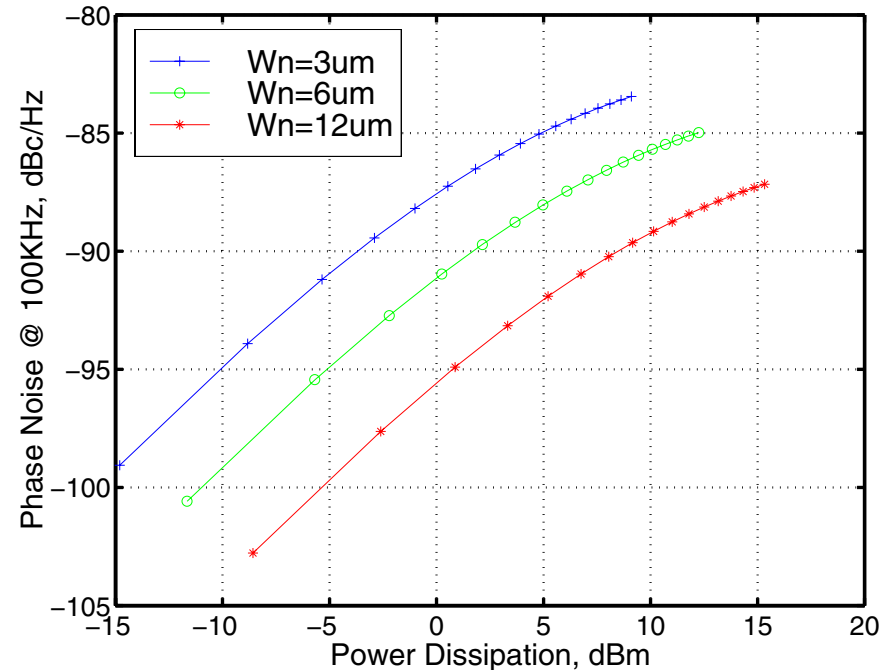
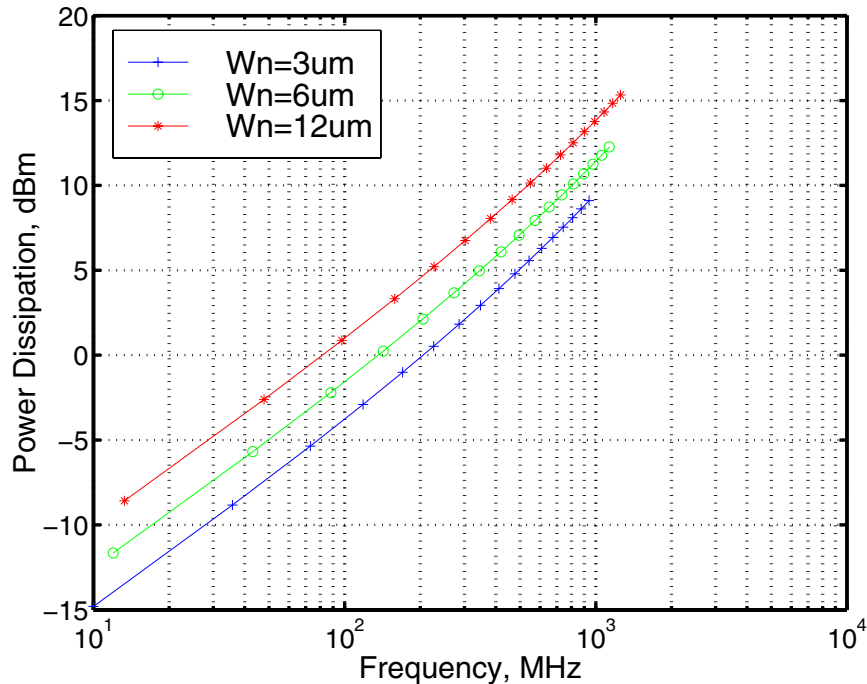


900 MHz CMOS RECEIVER [Darabi'00]

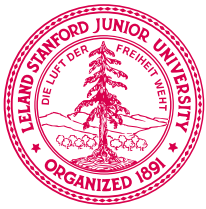
- Frequency synthesizers are implemented using Phase-locked Loops (PLLs).
- Major sources of power dissipation are the Voltage-controlled Oscillator (VCO) and the Frequency Divider.



Voltage-controlled Oscillator Trade-offs

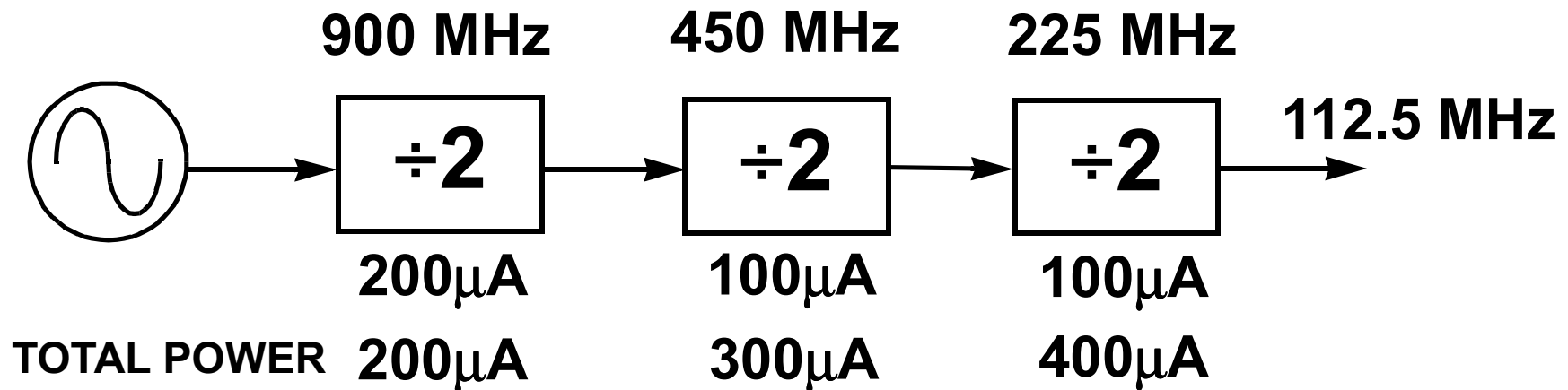


- The VCO's power dissipation is determined by the frequency of operation and the phase noise performance required.
- A PLL tracks phase noise of the reference within its loop bandwidth, relaxing the close-in phase noise requirements of the VCO.

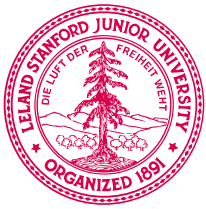


Frequency Divider Trade-offs

POWER INCREASES WITH DIVISION RATIO



- Better understanding of low-power techniques for frequency division is essential to reduce the overall power dissipation of integrated frequency synthesizers.
- We propose a technique in which power **decreases** with division ratio. Are you interested?



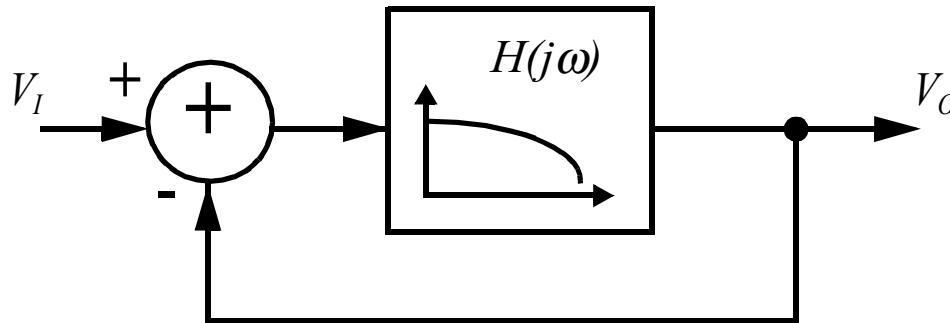
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How can a circuit oscillate?

• BADLY-DESIGNED FEEDBACK AMPLIFIER



Closed-loop Gain

$$A_V(j\omega) = \frac{H(j\omega)}{1 + H(j\omega)}$$

IF $H(j\omega_0) = -1$ **THEN** $\lim_{\omega \rightarrow \omega_0} A_V(j\omega) = \infty$

BARKHAUSEN CRITERIA

- Necessary conditions for oscillation
- Total phase shift around the loop is 360°
- Amplifies its own noise at ω_0
- Positive feedback or “regeneration”

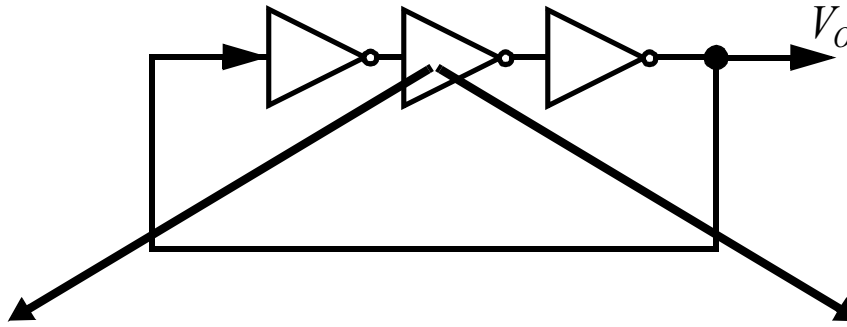
$$|H(j\omega_0)| \geq 1$$

$$\angle H(j\omega_0) = 180^\circ$$

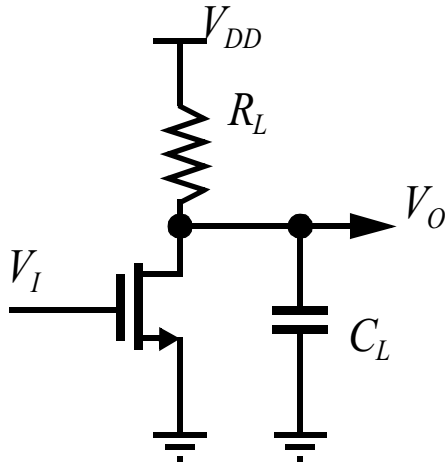


What is a Ring Oscillator?

- A RING OSCILLATOR CONSISTS OF A NUMBER OF GAIN STAGES IN A FEEDBACK LOOP



SINGLE-ENDED



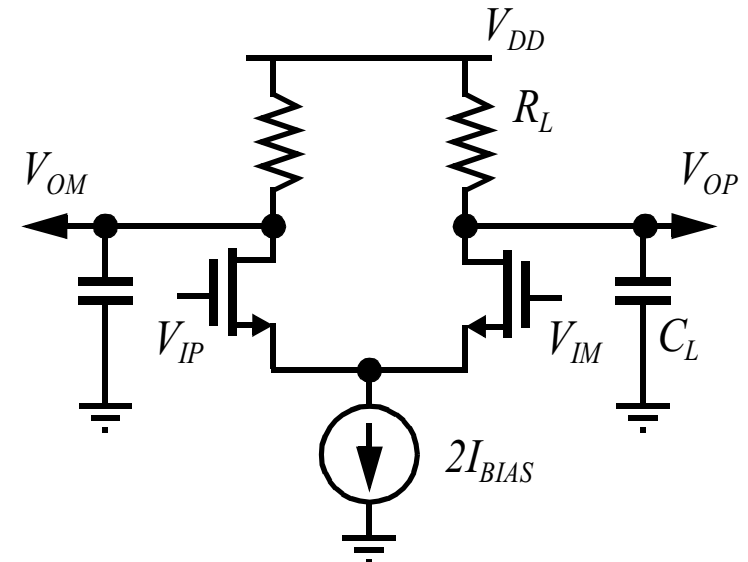
$$H_S(j\omega) = \frac{H_O}{1 + j\omega/\omega_P}$$

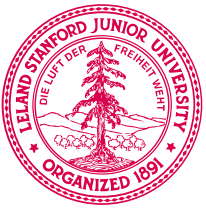
$$H_O = -g_m R_L \quad \omega_P = \frac{1}{R_L C_L}$$

$$C_L = C_{GS} + (2 + g_m R_L) C_{GD} + C_{DB}$$

- Neglect feedforward zero $+g_m/C_{GD}$

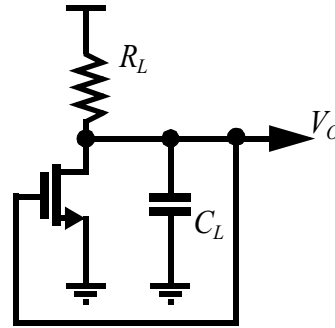
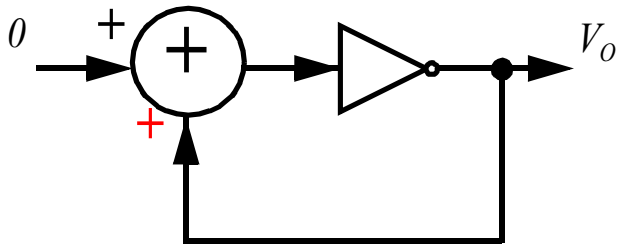
DIFFERENTIAL





Evolution of the Ring Oscillator

1 STAGE

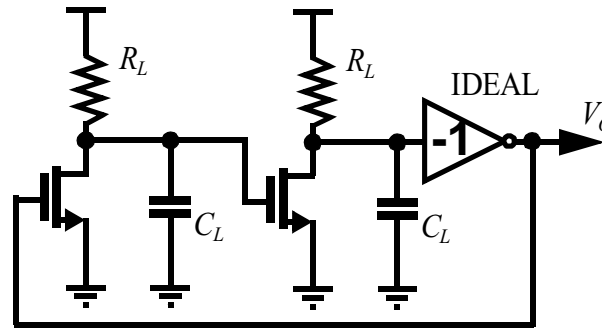
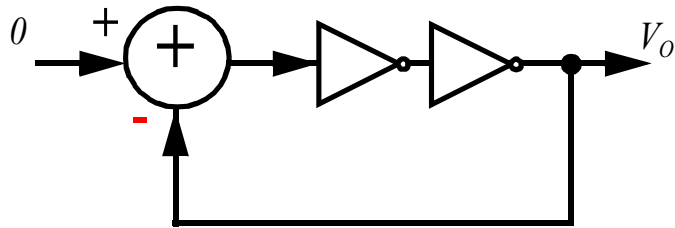


$$H(j\omega) = \frac{H_O}{1 + j\omega/\omega_P}$$

$$\angle H(j\omega)|_{\infty} = 90^\circ$$

INSUFFICIENT PHASE

2 STAGES

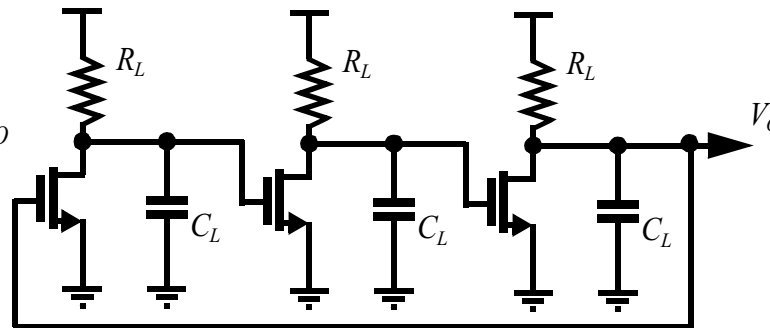
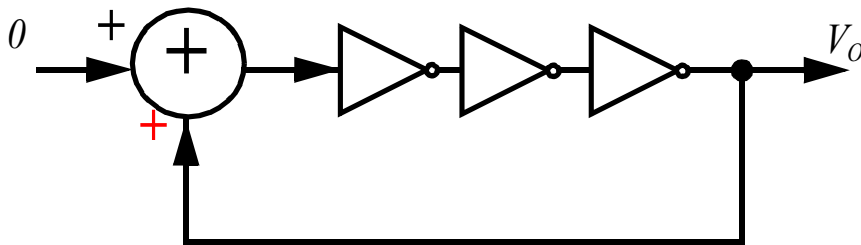


$$H(j\omega) = \frac{H_O^2}{(1 + j\omega/\omega_P)^2}$$

$$\angle H(j\omega)|_{\infty} = 180^\circ$$

INSUFFICIENT GAIN

3 STAGES



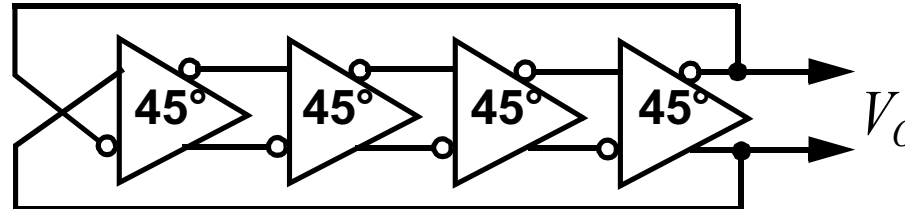
$$\angle H(j\omega)|_{\infty} = 270^\circ$$

IT WORKS!



Evolution of the Ring Oscillator (II)

4-STAGE DIFFERENTIAL RING OSCILLATOR



- EACH STAGE CONTRIBUTES 45° @ ω_o
- EACH POLE CONTRIBUTES 45° @ ω_p

IN GENERAL

$$H(j\omega) = \frac{H_o^n}{(1 + j\omega/\omega_p)^n}$$

PHASE CONDITION

$$\angle H(j\omega_o) = n \cdot \text{atan}\left(\frac{\omega_o}{\omega_p}\right) = \pi$$

GAIN CONDITION

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

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

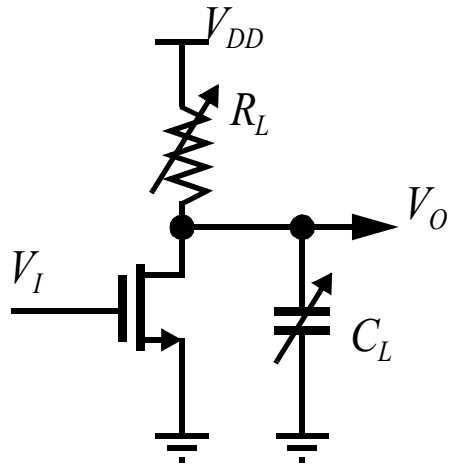
$n > 2$

LARGE SWING (AMPLITUDE LIMITED)

$$f_{osc} = \frac{1}{2nT_D} < f_o \quad \text{WHERE } T_D \propto \tau_P$$



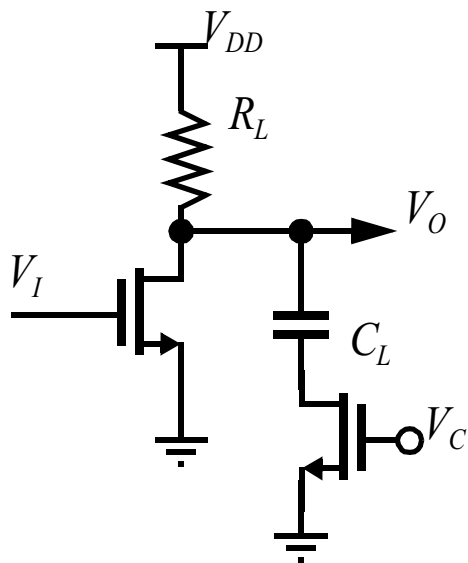
Voltage-Controlled Ring Oscillator



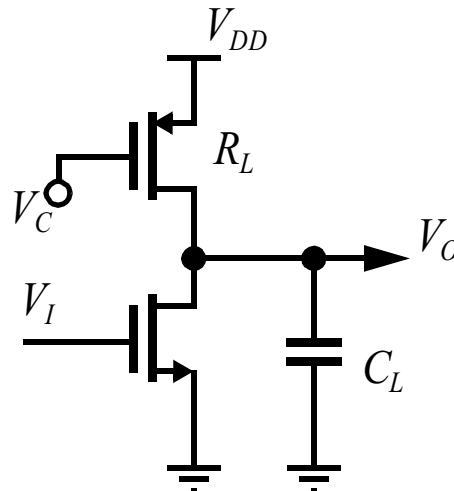
- Delay of each stage T_D is tuned by control input.
- Change delay by varying capacitance or resistance at each stage.

$$T_D \propto R_L C_L \quad \omega_P = \frac{1}{R_L C_L}$$

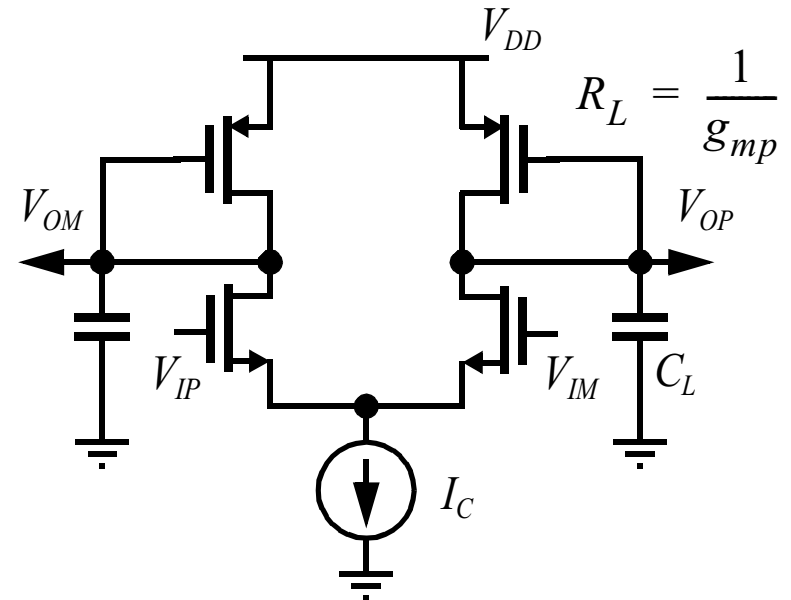
CAPACITIVE TUNING

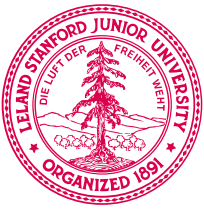


TRIODE LOAD



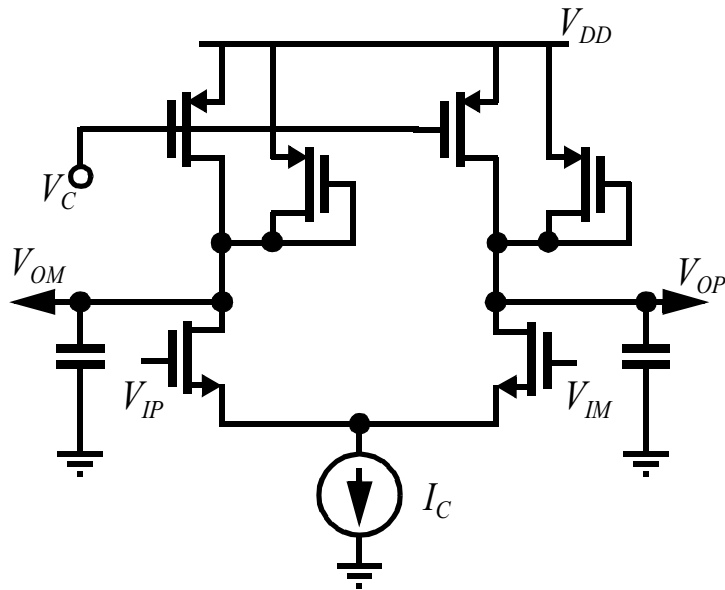
DIODE-CONNECTED LOAD



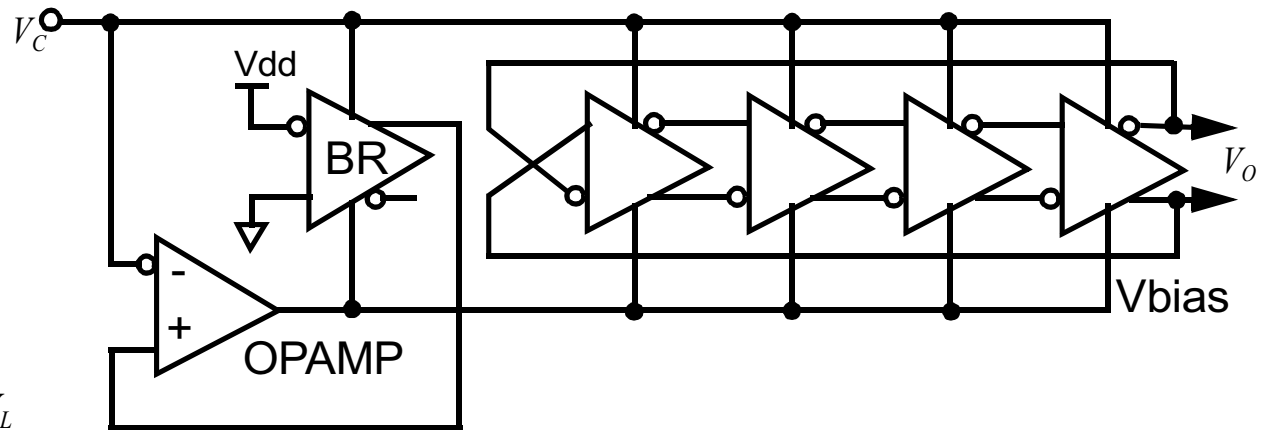
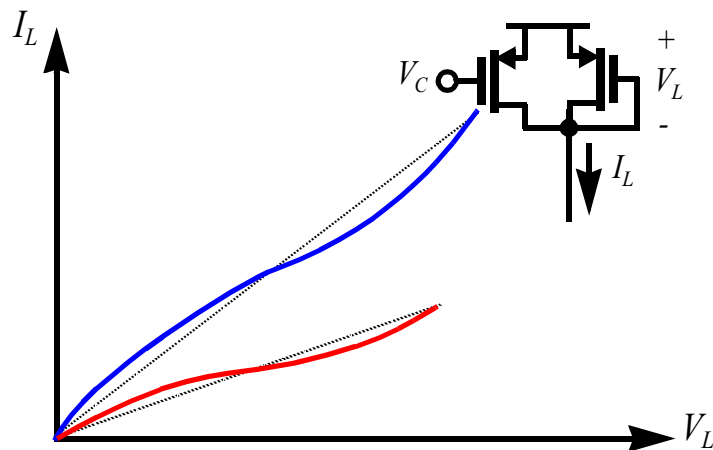


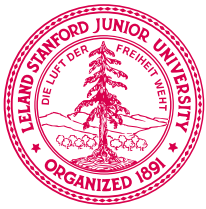
Voltage-Controlled Ring Oscillator (II)

SYMMETRIC LOAD [MANEATIS'94]



- Use buffers with replica-feedback biasing.
- V_C changes the bias I_C of the buffers.
- Replica bias ensures load symmetry by forcing the maximum single-ended swing $V_S = V_{dd} - V_C$
- Good supply noise rejection





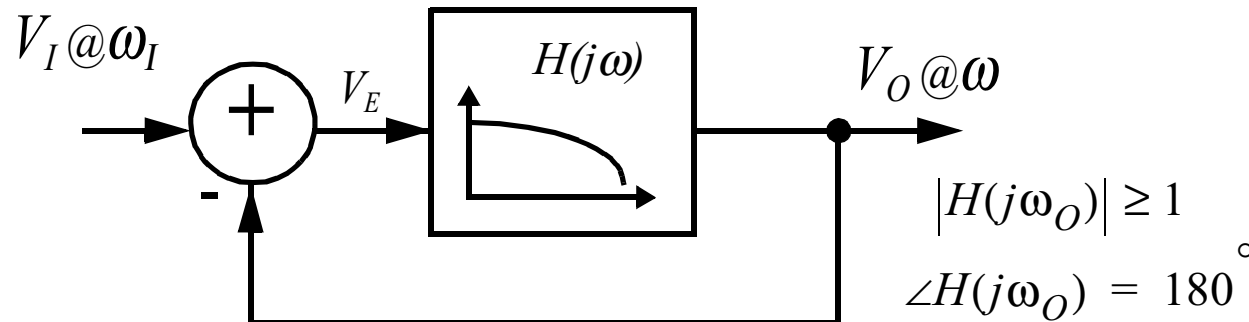
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What is Injection Locking? [Adler 1946]

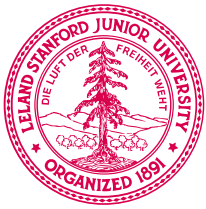
OSCILLATOR OUTPUT SYNCHRONIZES TO INJECTED SIGNAL



ASSUME $\omega_I \approx \omega_O$
 $V_I \ll V_O$

Fast Amplitude Limiting Mechanism

- **IF** $V_I = 0$ **THEN** $\omega = \omega_O$
- **IF** $V_I \neq 0$ **THEN** ω shifts from free-running frequency, ω_O .
- Frequency shift is proportional to V_I/V_O .

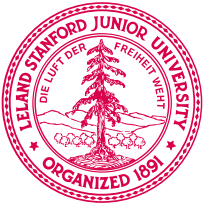


Locking Range of Injection-locked Oscillator

$$\left| \frac{\Delta\omega_O}{\omega_O} \right| < \frac{V_I}{V_O} \cdot \frac{2}{n \sin\left(\frac{2\pi}{n}\right)}$$

$$\Delta\omega_O = \omega_O - \omega_I$$

- Proportional to V_I/V_O .
- Inversely proportional to number of stages, n .
- Only valid for $V_I \ll V_O$



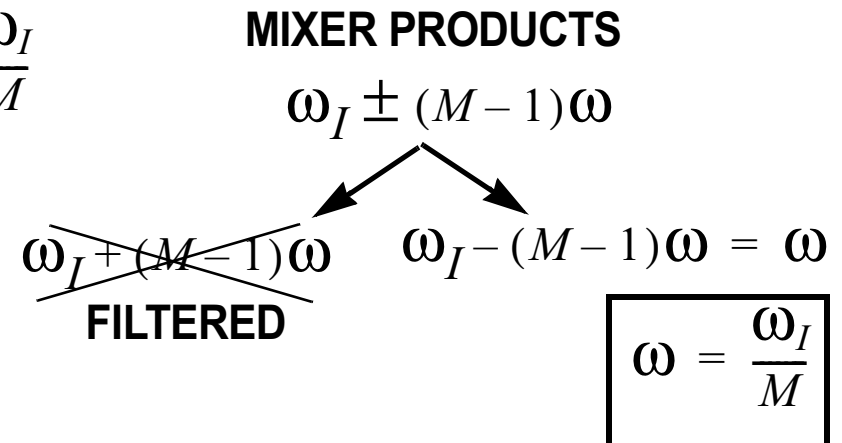
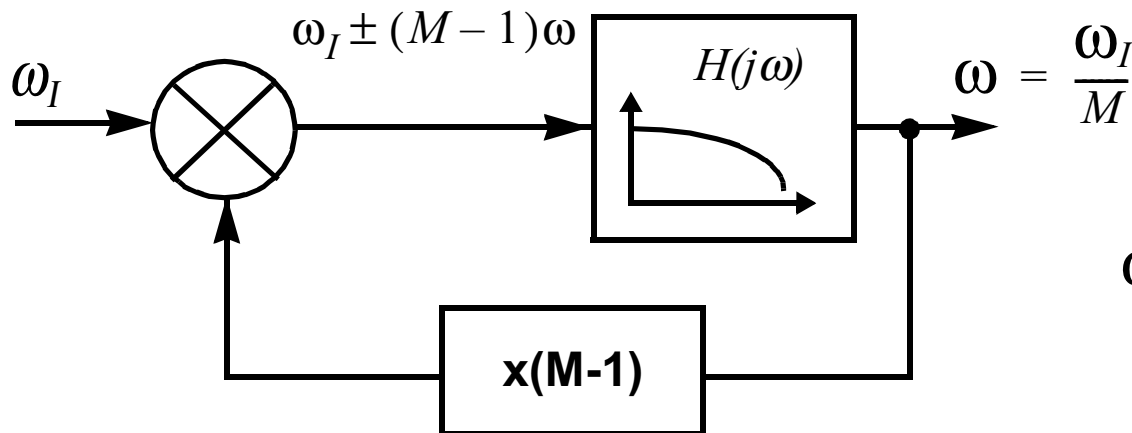
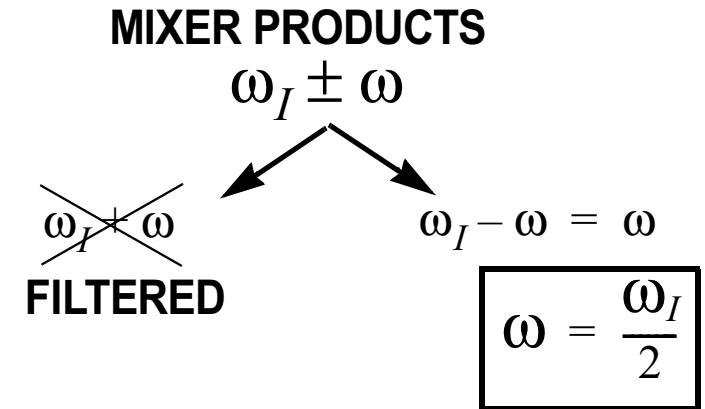
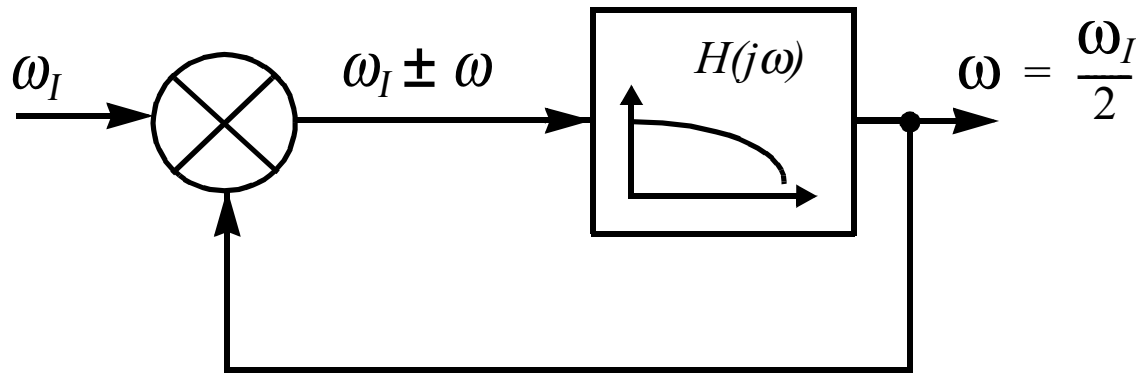
Superharmonic Injection Locking

- An oscillator can be injection-locked to a harmonic of the free-running oscillation frequency.
- This principle is used by all regenerative frequency dividers.
- Regenerative dividers are commonly used in applications where the frequency of operation is very high, beyond what can be achieved with flip-flop based circuits.
- Efforts at frequencies beyond 5 GHz have been reported using injection-locking to implement divide-by-2 prescalers in CMOS, and Si-BJT technologies.
- Commonly used at mm-wave frequencies in GaAs and SiGe

We want to exploit injection locking to achieve low-power frequency division.



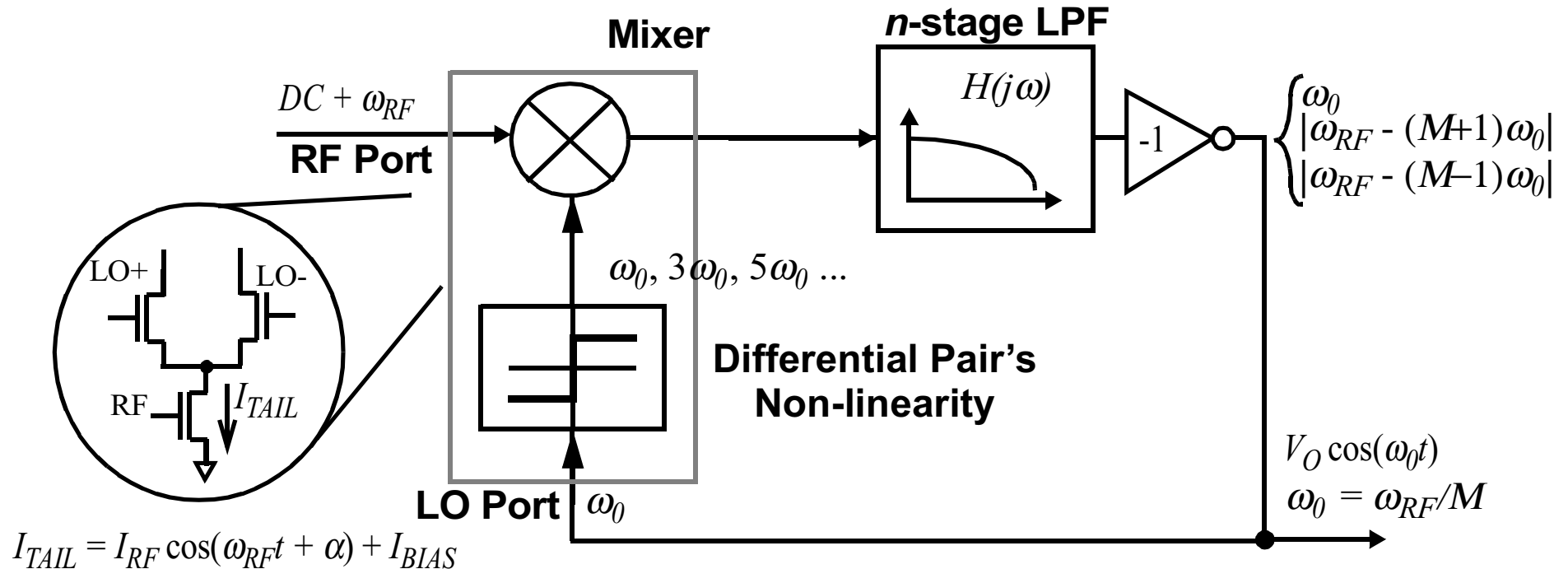
Regenerative Divider [Miller 1939]



- Can achieve division ratios greater than two by using a frequency multiplier in the feedback.
- Frequency multiplier can represent non-linearities present in the circuit.
- We can describe an Injection-locked Frequency Divider (ILFD) using a generalized mixer-



Generalized Model for Injection-locked Divider



MIXER

- Single-balanced mixer based on a differential-pair
- Injected ω_{RF} into the tail device (“Injector”), which produces an RF current that adds to I_{BIAS}
- RF current may include a DC component and all harmonics of ω_{RF} . For now, we will ignore this effect.

LOOP FILTER

- Mixer products are low-pass filtered and amplified by $H(j\omega)$
- Suppress mixer products $> \omega_0$
- For small n , the output voltage V_O is sinusoidal.

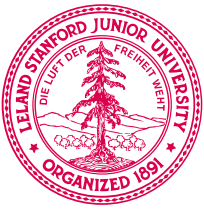


Generalized Model for Injection-locked Divider (II)

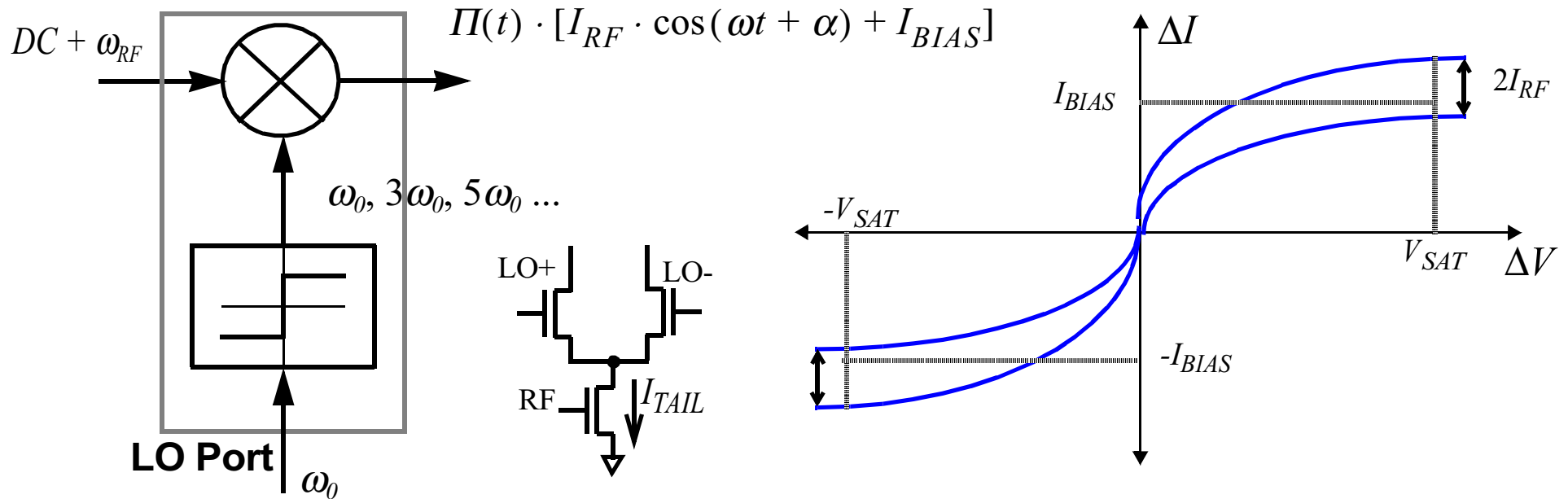
Use describing function analysis to determine the open-loop transfer characteristic's phase and magnitude components.

ASSUMPTIONS

- 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.
- A large amplitude is also required to excite the Mixer's LO port non-linearity, which is the mechanism that makes possible division ratios greater than two.



Mixer

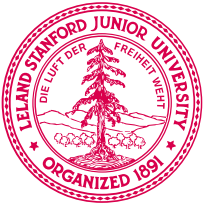


ASSUME $V_O \gg V_{SAT}$ (SWITCH HARD)

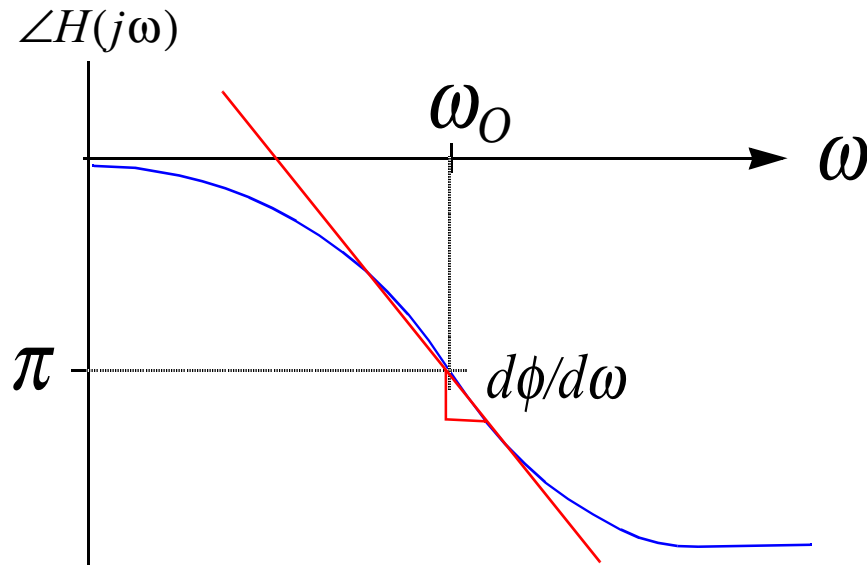
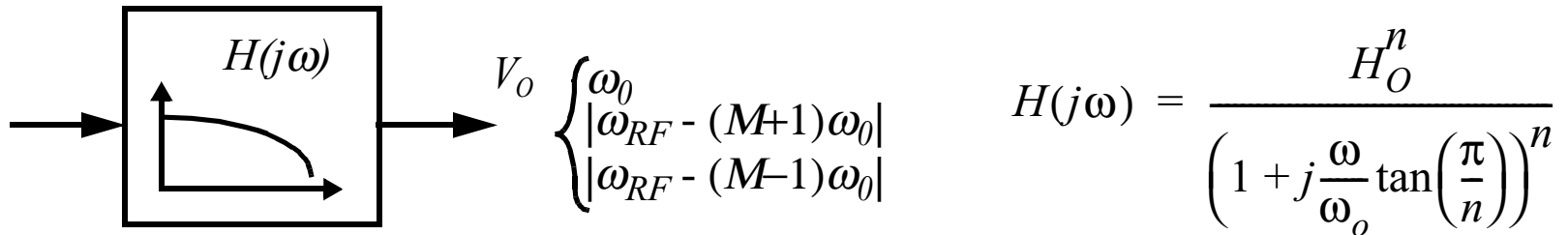
Fourier Coefficients of Mixing Function (Square Wave)

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

- The differential-pair's transfer characteristic is non-linear with odd symmetry.
- When excited by ω_0 , the mixer's non-linearity produce odd harmonics at $3\omega_0$, $5\omega_0$, etc.
- The total current I_{TAIL} is modulated by ω_0



Loop Filter



LINEARIZE PHASE OF $H(j\omega)$

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

$$\Delta\omega = \omega - \omega_0$$

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



Locking Range of Injection-locked Ring Oscillator

WRITE PHASE EXPRESSION AROUND THE LOOP

$$\text{atan} \left(\frac{\eta_i (C_{M-1} - C_{M+1}) \sin \alpha}{C_1 + \eta_i (C_{M-1} + C_{M+1}) \cos \alpha} \right) = \angle H(j\omega) - \pi$$

MIXER

FILTER

$$\eta_i = \frac{I_{RF}}{2I_{BIAS}}$$

INJECTION EFFICIENCY

LOCKING RANGE

$$\frac{\Delta\omega}{\omega_0} \cong \frac{4}{n \sin\left(\frac{2\pi}{n}\right)} \text{atan} \left(\frac{k_0}{\sqrt{1 - k_1^2}} \right)$$

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

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

Trade-offs

- The locking range is a 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.



What Happens When Assumptions Break Down

1. Limited Mixer Gain - Switching function is not a square wave.

(Swing ratio should be large, $\rho_s = V_0/V_{SAT} \gg 1$)

- As ρ_s gets smaller, the square wave assumption is no longer valid and the coefficient ratios C_k/C_1 are significantly smaller.

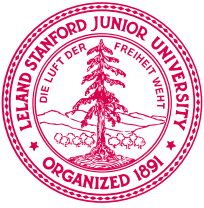
2. Limited Injection Efficiency - Due to short-channel effects, velocity saturation, device non-linearity.

- Due to Injector non-linearities, I_{DC} rises for large injected signals ($I_{DC} > I_{BIAS}$). An increase of I_{DC} also affects V_{SAT} , reducing the swing ratio.

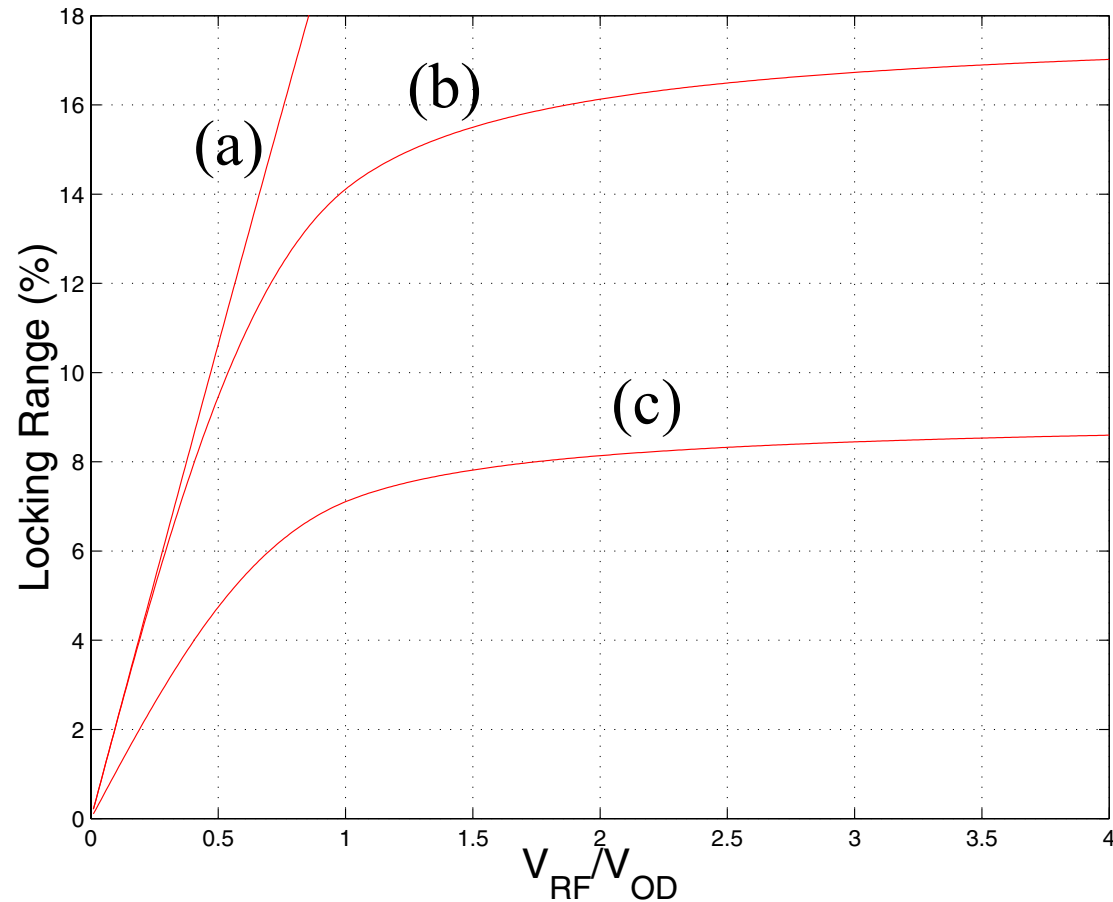
$$\eta_i = \frac{I_{RF}}{2I_{DC}} = \frac{V_{RF}}{2V_{OD, TAIL}} \cdot \gamma \quad I_{DS} = K \cdot (V_{RF} + V_{OD, TAIL})^\gamma$$

3. Mixer Tail Node Parasitics - Due to tail drain junction and diffpair source junction.

- Parasitic capacitance at the drain of the tail device provides a shunt path for I_{RF} reducing η_i at high frequencies.



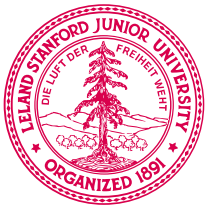
5-stage Ring Oscillator, modulo-8 Divider



(a) Ideal (phase-limited) case

(b) Compression due to Injector non-linearity

(c) Effect of Injector non-linearity and drain junction parasitics (50% RF current loss)

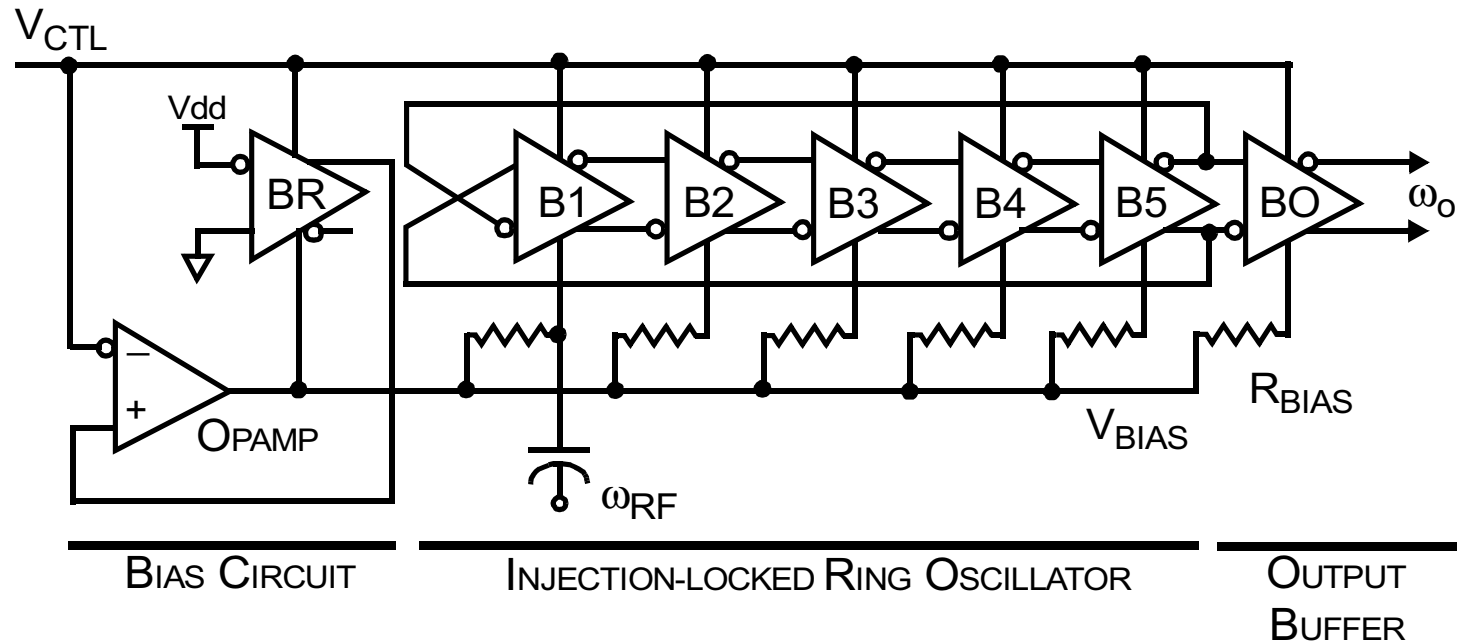


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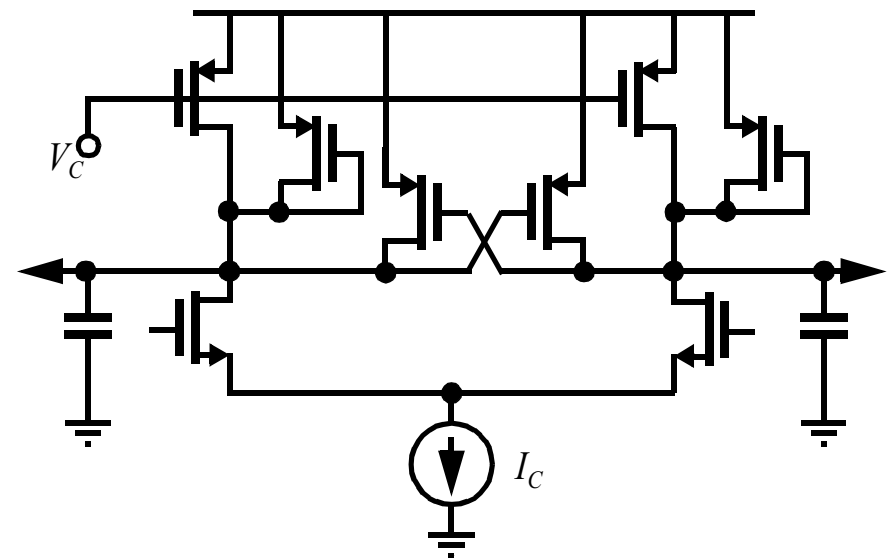
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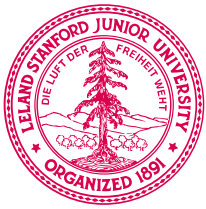


5-stage Injection-locked Ring Oscillator Divider



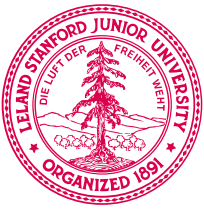
- Modified cross-coupled symmetric load buffers were used for their good supply noise rejection and low $1/f$ noise upconversion characteristics.
- We injected the RF signal at the tail current source of the first buffer, using it as a single-balanced mixer.
- The buffer stages behave as the multipole filter $H(j\omega)$ that contribute the gain and phase shift required to sustain the oscillation.



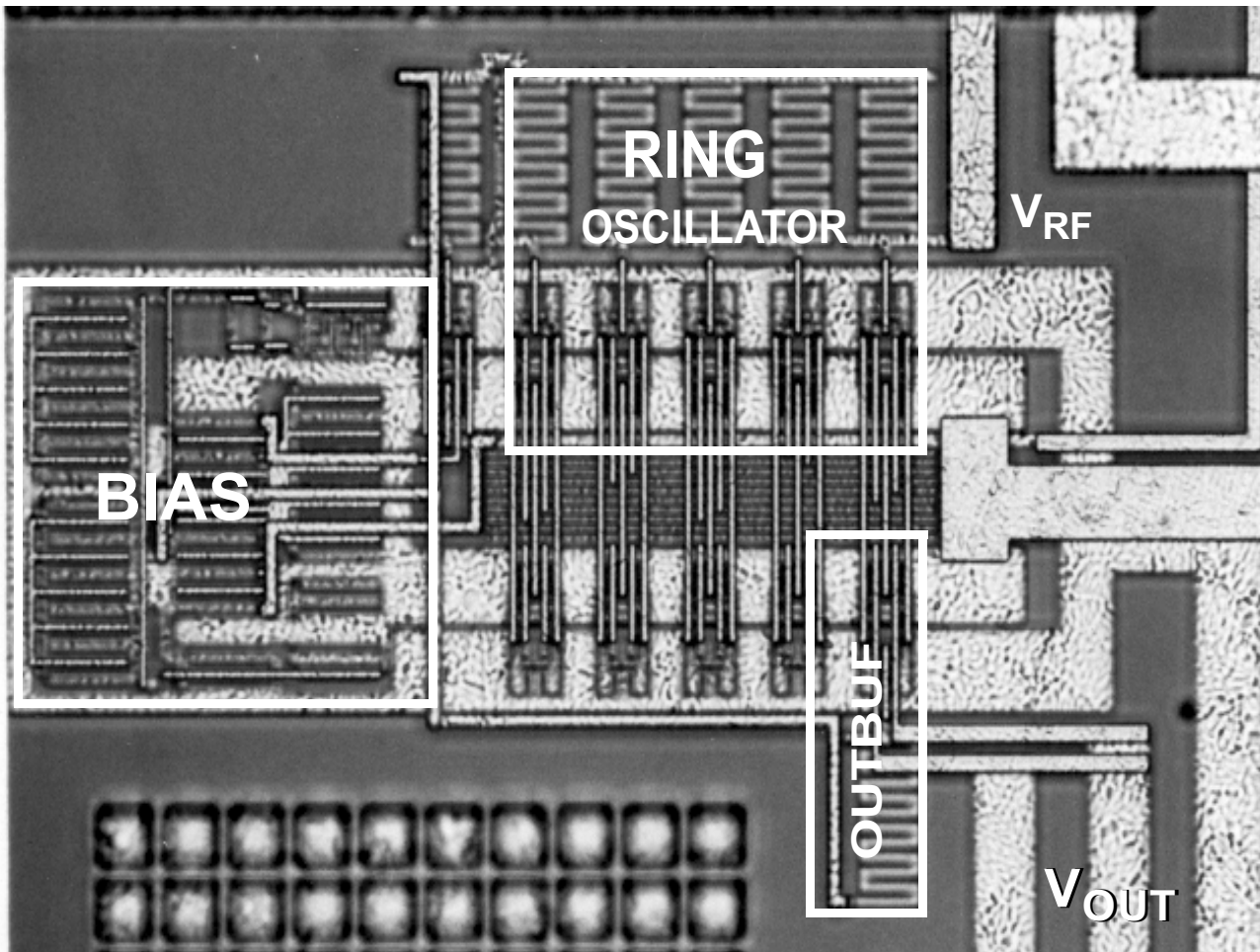


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- Conclusion



Die Micrograph: 5-stage Ring Oscillator Divider



- Two ring oscillators were designed, with 3 and 5 buffer stages respectively.
- Layout is symmetrical and load balanced to avoid any skewing between the phases.
- 0.24- μm CMOS
- 0.012 mm^2 of area

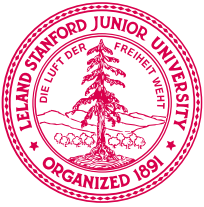


Results

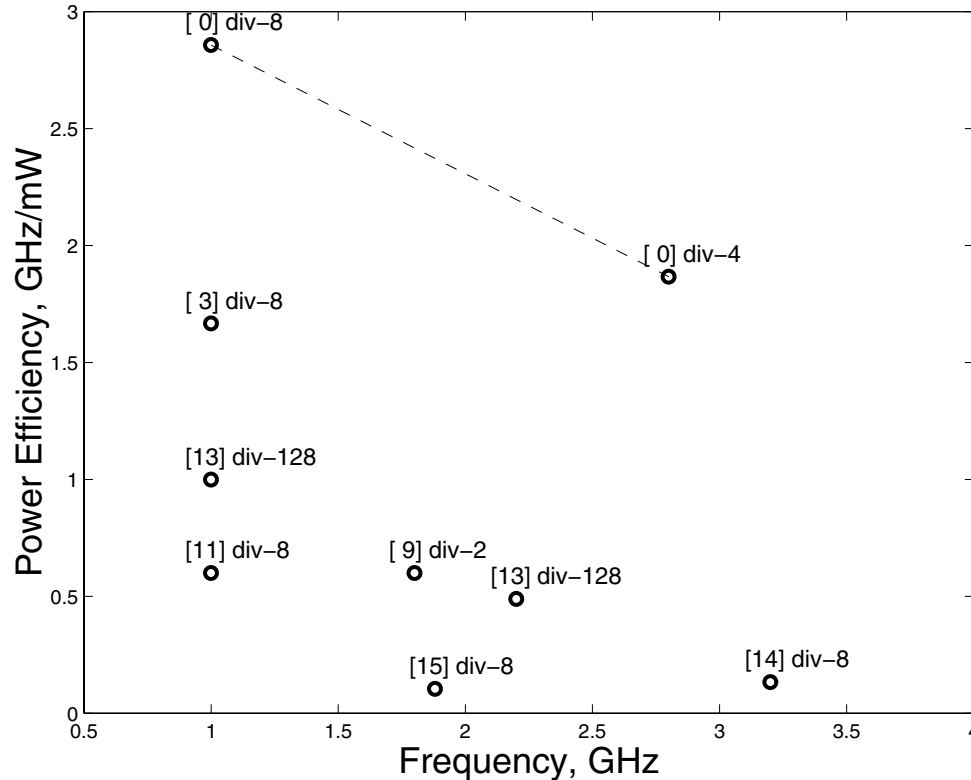
Measurements

	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
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
I _{core}	233 μ A	331 μ A
I _{bias}	108 μ A	661 μ A
Core power	350 μ W	993 μ W
Power efficiency	2.86 GHz/mW	2.82 GHz/mW

- Swing is smaller than expected, hence the locking range is smaller than predicted.
- Locking range is not symmetric around the free-running frequency of the ILFD, specially at higher injected power levels. This behavior is due to the increase of I_{DC} with the injected signal.

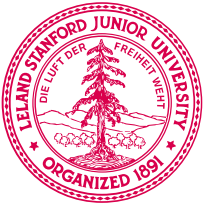


Power Efficiency of Injection-locked Ring Oscillator



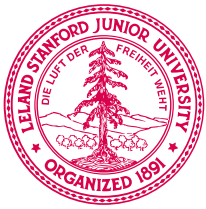
- Power efficiency is the ratio of the divider's maximum operation frequency to its power dissipation expressed in GHz/mW.
- To achieve a fair comparison of the available data, only the "core" divider circuit is taken into consideration
- 5-stage (mod-8), 2.86 GHz/mW @1GHz.
- 3-stage, (mod-4), 2.82 GHz/mW @2.8GHz.

EXCEED ALL PUBLISHED RESULTS AT COMPARABLE FREQUENCIES



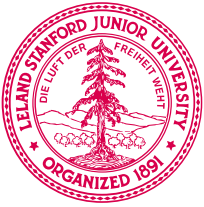
What We Learned

- Need to scale down the Injector to lower the parasitics, thus increasing the injection efficiency.
- The tail node parasitics can also be cancelled by resonating with an inductor (shunt-peaking), but this is not practical at sub-GHz frequencies.
- Increase the output swing and the W/L ratio of the Injector, hence increasing the swing ratio. This should be weighted against the resultant increase in parasitic capacitance and power dissipation.
- While a flip-flop based divider uses more power as we add more stages, the injection-locked divider uses less power for higher division ratios (every stage is operating at ω_0).



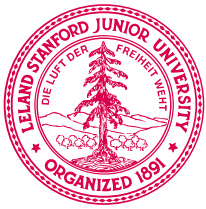
Outline

- Goals
- Ring Oscillator Overview
- Injection Locking Theory
- Circuit Implementation
- Measured Results
- ***Conclusion***



Conclusion

- Reviewed the operation of voltage-controlled CMOS ring oscillators.
- 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 the injection locking phenomena 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.
- Achieved the highest power efficiency (2.86 GHz/mW) ever



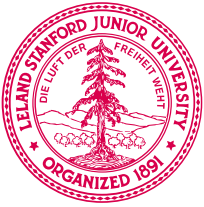
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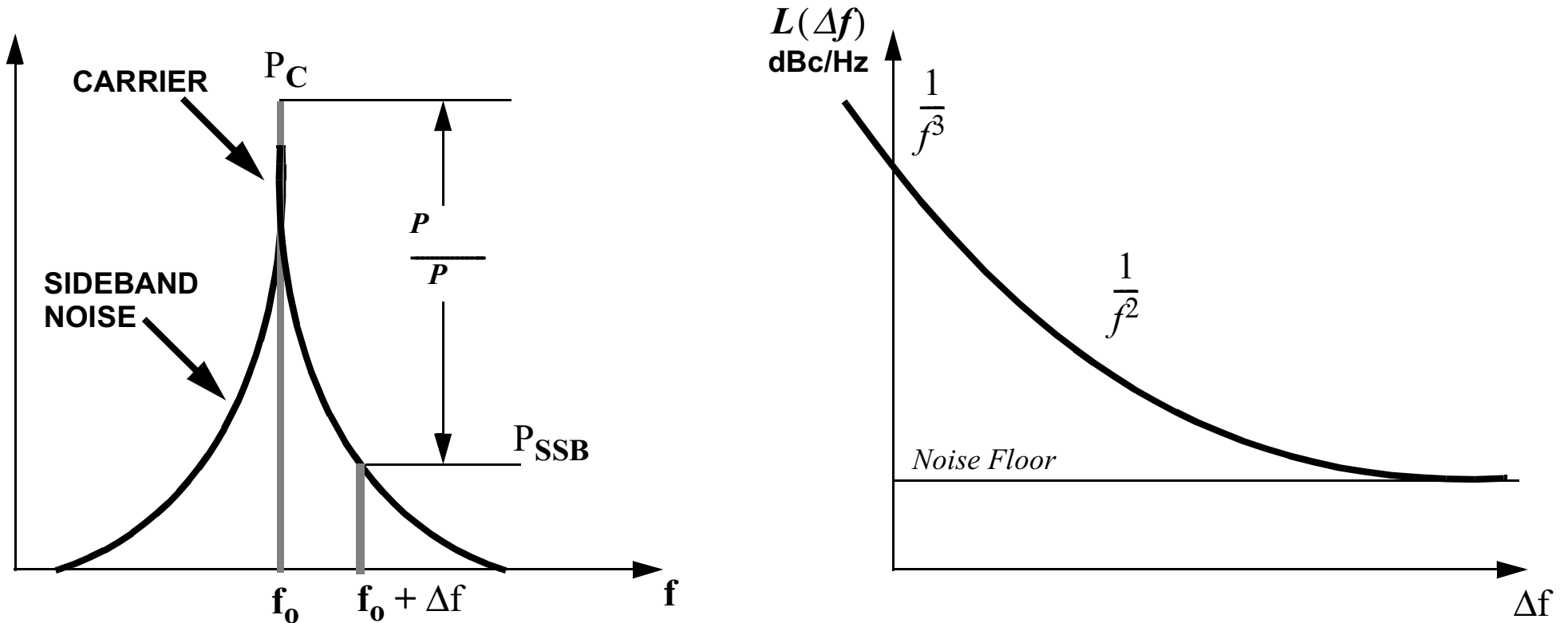


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What is Phase Noise?

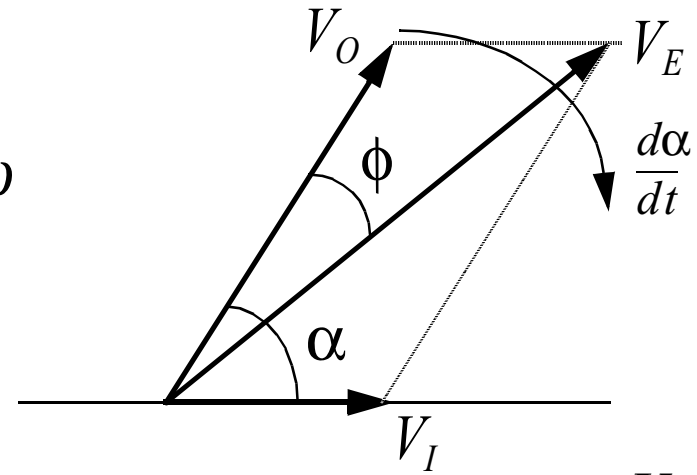
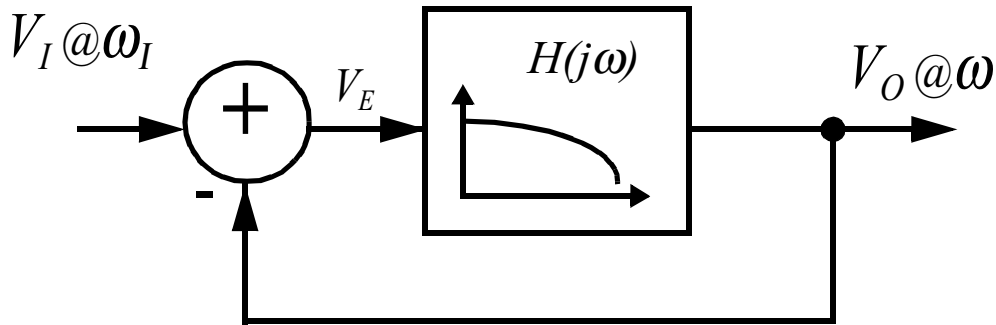


- Undesirable phase fluctuations due to intrinsic device noise
- Output power is not concentrated at the carrier frequency alone
- Phase noise is represented as a ratio of power in 1Hz bandwidth in one sideband to the power of the carrier.
- Specified in dBc/Hz at a frequency offset from the carrier.



What is Injection Locking? [Adler 1946]

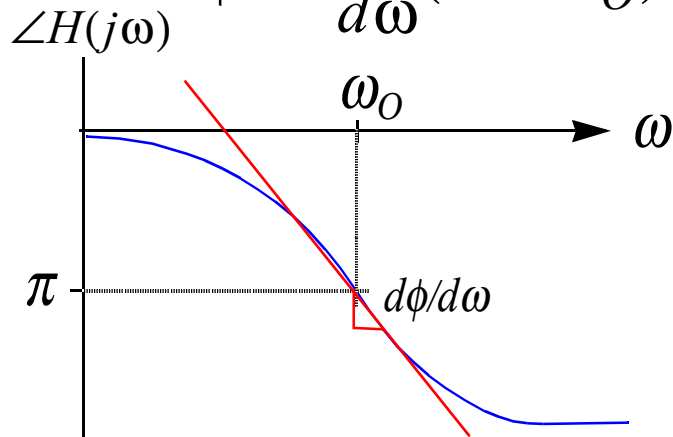
ASSUME $\omega_I \approx \omega_O$ AND $V_I \ll V_O$



$$\phi = \angle H(j\omega) + \pi$$

LINEARIZE PHASE

$$\phi = \frac{d\phi}{d\omega}(\omega - \omega_O)$$



$$\omega = \omega_I + \frac{d\alpha}{dt} \quad \phi = -\frac{V_I}{V_O} \sin \alpha$$

$$\omega = \frac{-V_I/V_O \sin \alpha}{d\phi/d\omega} + \omega_O$$

- Output frequency shifts from free-running frequency
- **IF** $V_I = 0$ **THEN** $\phi = 0$ and $\omega = \omega_O$



Locking Range of Injection-locked Oscillator

1. FREQUENCY SHIFT

$$\omega = \frac{-V_I/V_O \sin \alpha}{d\phi/d\omega} + \omega_O$$

$$\omega = \omega_I + \frac{d\alpha}{dt}$$



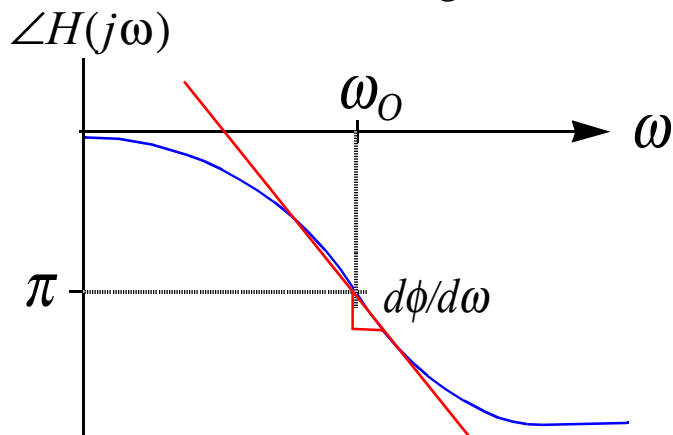
2. DIFFERENTIAL EQUATION

$$\frac{d\alpha}{dt} = \frac{-V_I/V_O \sin \alpha}{d\phi/d\omega} + \Delta\omega_O$$

$$\Delta\omega_O = \omega_O - \omega_I$$

3. LINEARIZE PHASE OF $H(j\omega)$

$$\frac{d\phi}{d\omega} \cong \frac{n}{2\omega_O} \sin\left(\frac{2\pi}{n}\right)$$



4. STEADY-STATE SOLUTION

FOR $\frac{d\alpha}{dt} = 0$

LOCKING RANGE

$$\left| \frac{\Delta\omega_O}{\omega_O} \right| < \frac{V_I}{V_O} \cdot \frac{2}{n \sin\left(\frac{2\pi}{n}\right)}$$