Phase Noise in CMOS Differential LC Oscillators

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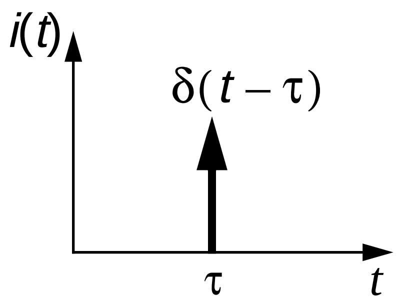
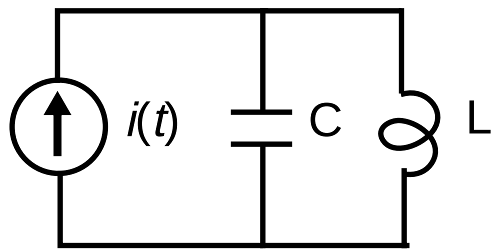
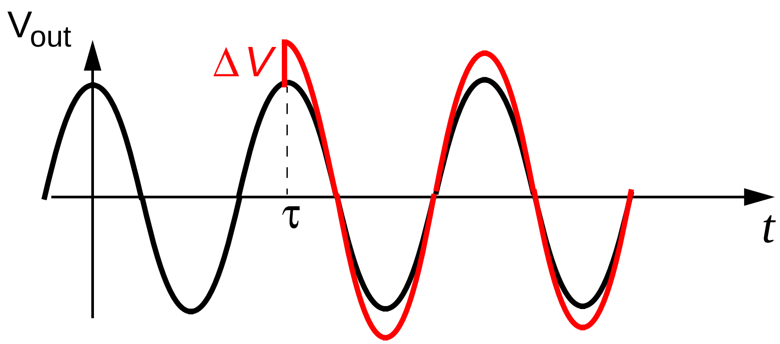
Outline

- ***Introduction and Definitions***
- Tank Voltage
- Noise Sources
- Effect of Tail Current Source
- Measurement Results
- Conclusion

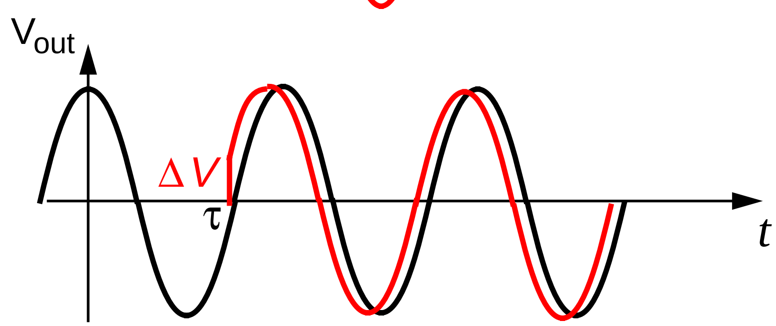
Oscillators Are Time-Variant Systems







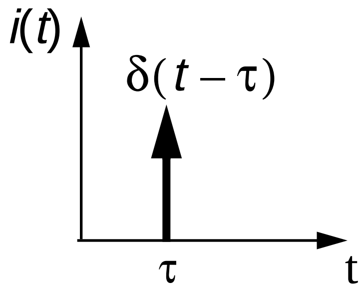
Impulse injected at the peak of amplitude.

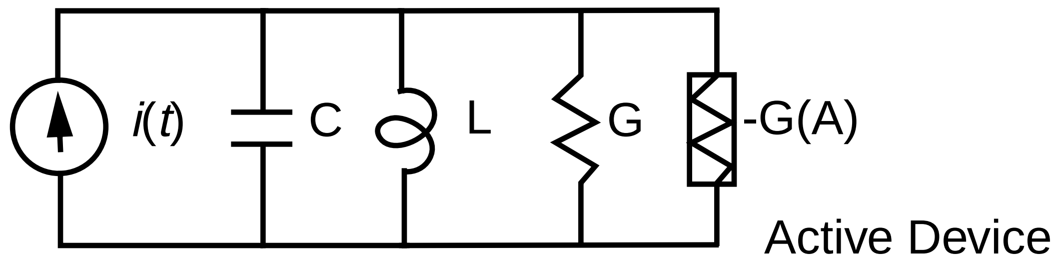


Impulse injected at zero crossing.

Even for an ideal LC oscillator, the phase response is *Time Variant.*

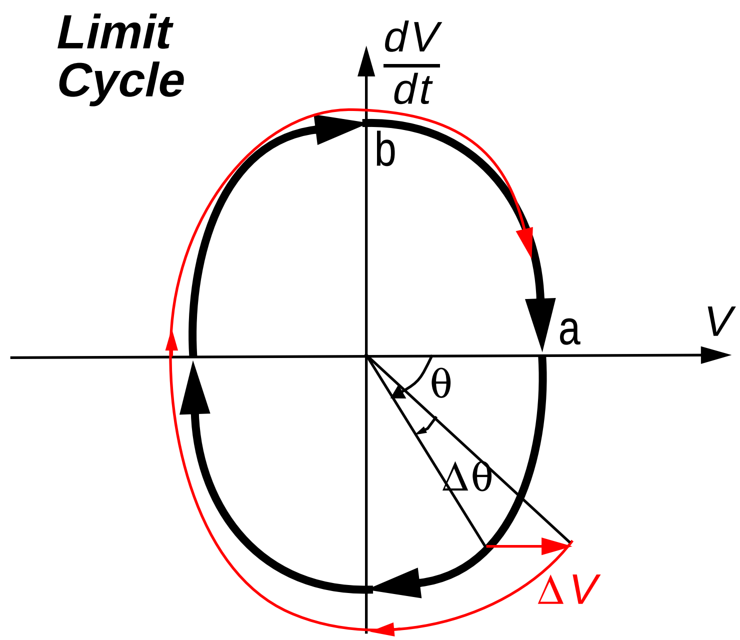
Amplitude Restoring Mechanism





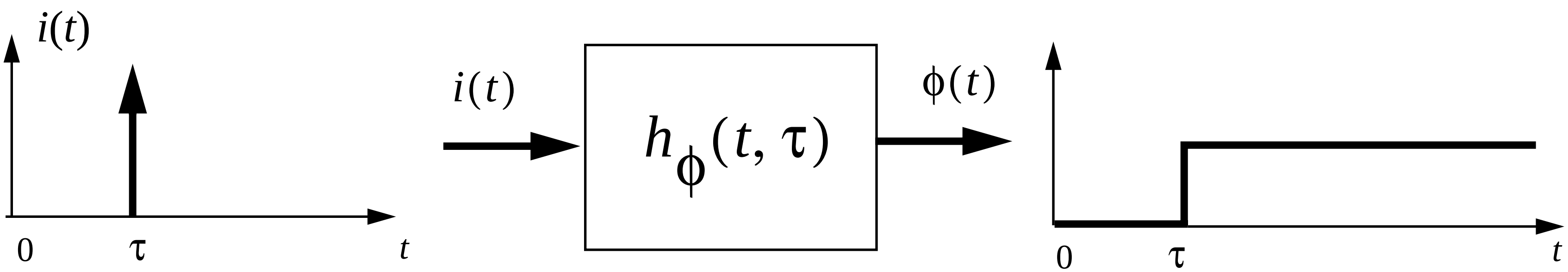
Once Introduced, phase error persists indefinitely.

Non-linearity quenches amplitude changes over time.



Phase Impulse Response

The phase impulse response of an arbitrary oscillator is a time varying step.



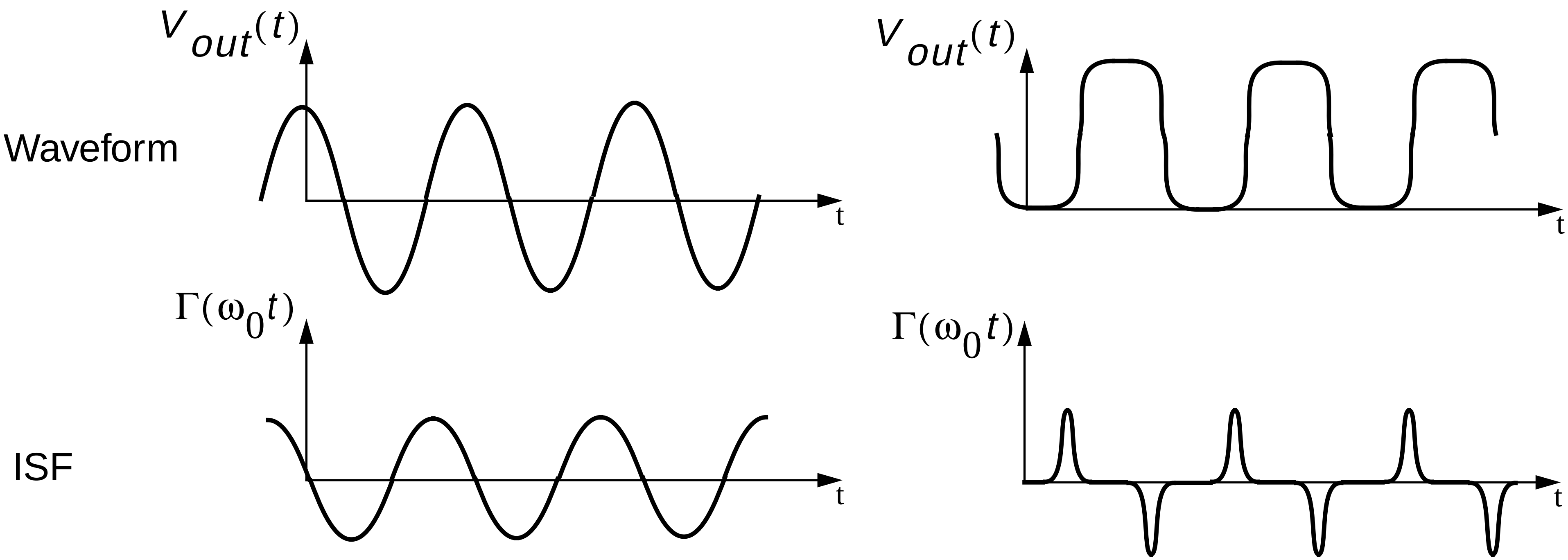
The unit impulse response is:

$$h_\phi(t, \tau) = \frac{\Gamma(\omega_o \tau)}{q_{max}} u(t - \tau)$$

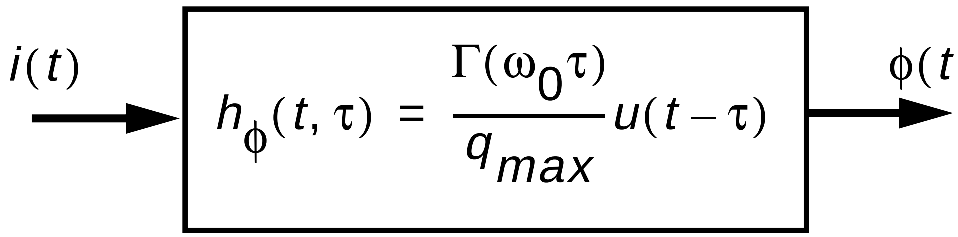
$\Gamma(x)$ is a dimensionless function periodic in 2π, describing how much phase change results from applying an impulse at time: $t = T\frac{x}{2\pi}$

Impulse Sensitivity Function (ISF)

The ISF quantifies the sensitivity of every point in the waveform to perturbations.



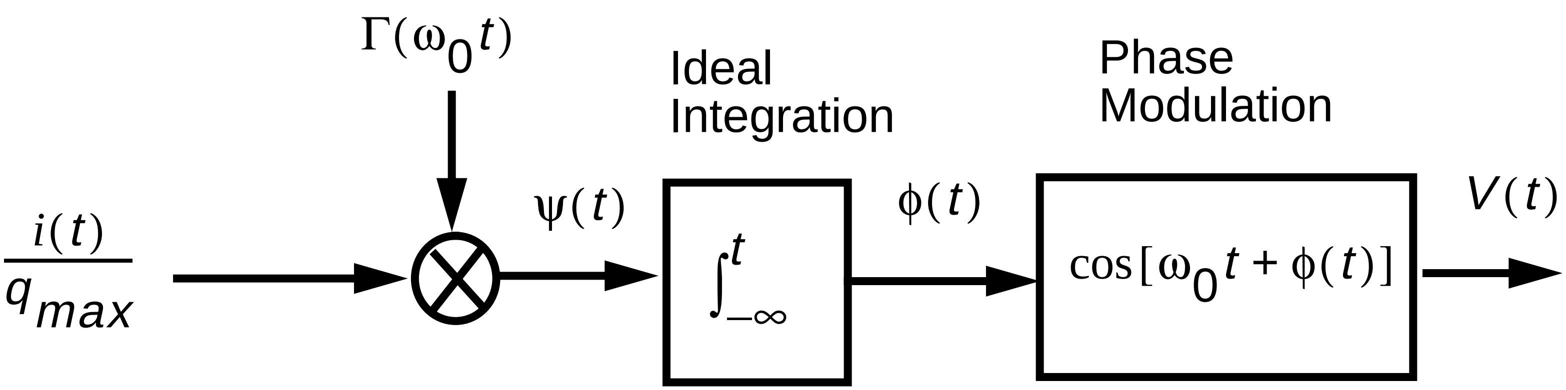
Phase Response to an Arbitrary Source



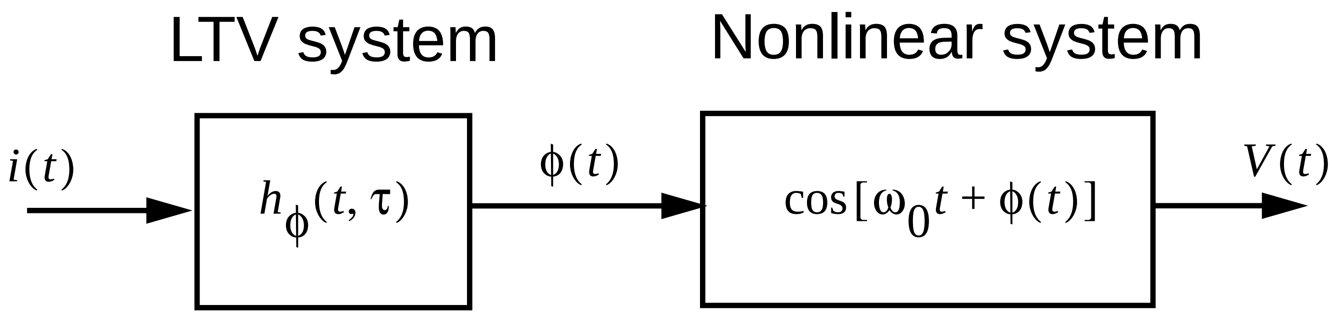
Superposition Integral:

$$\phi(t) = \int_{-\infty}^{\infty} h_\phi(t, \tau) i(\tau) d\tau = \frac{1}{q_{max}} \int_{-\infty}^{t} \Gamma(\omega_0 \tau) i(\tau) d\tau$$

Equivalent representation:



Phase Noise Due to White Noise



For a white input noise current with spectral density of $\frac{\overline{i_n^2}}{\Delta f}$,

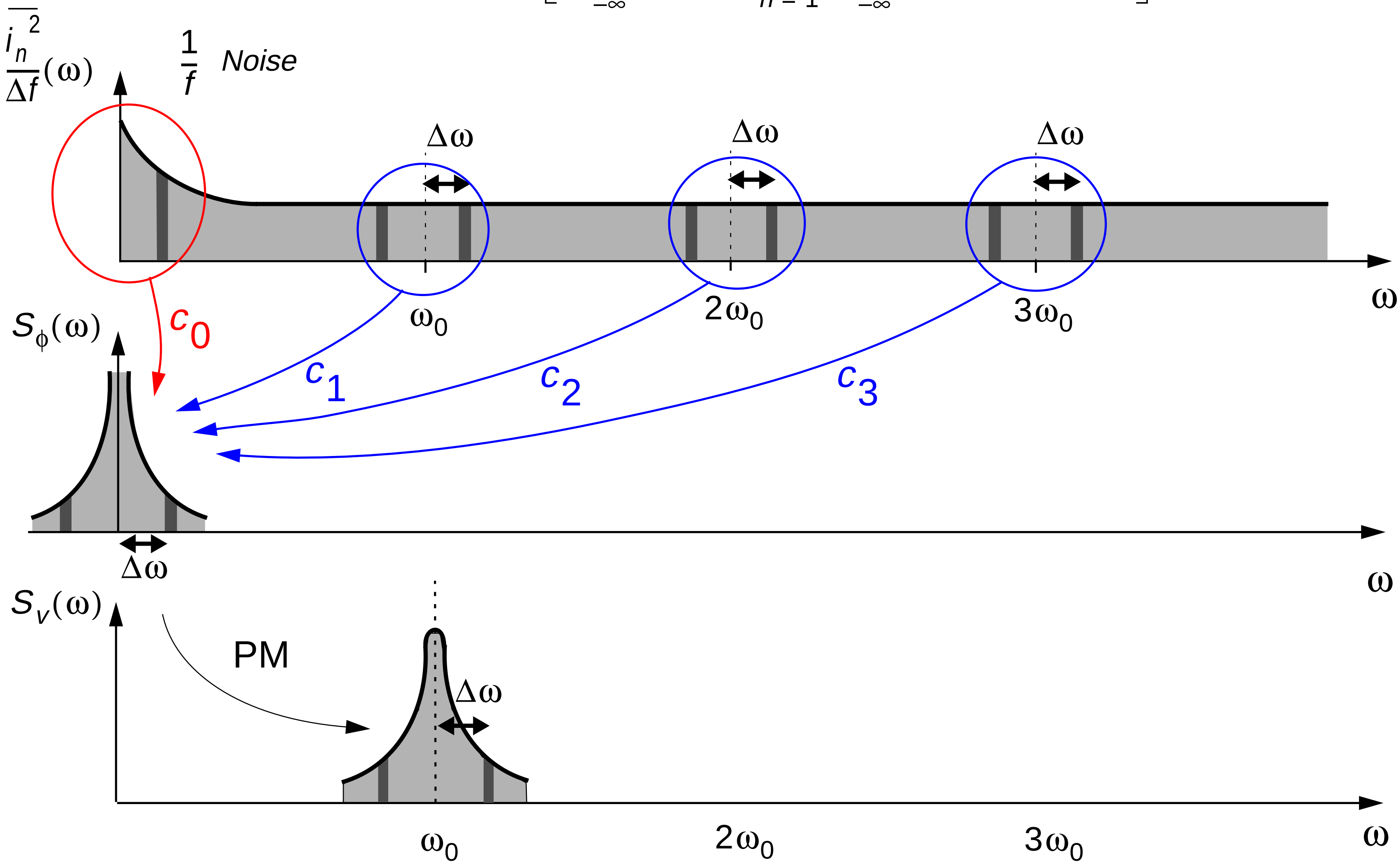
the phase noise sideband power below the carrier at an offset of $\Delta\omega$ *is:*

$$L\{\Delta\omega\} = \frac{\Gamma_{rms}^2}{q_{max}^2} \cdot \frac{\overline{i_n^2}/\Delta f}{2\Delta\omega^2}$$

where Γ_{rms} *is the rms value of the ISF.*

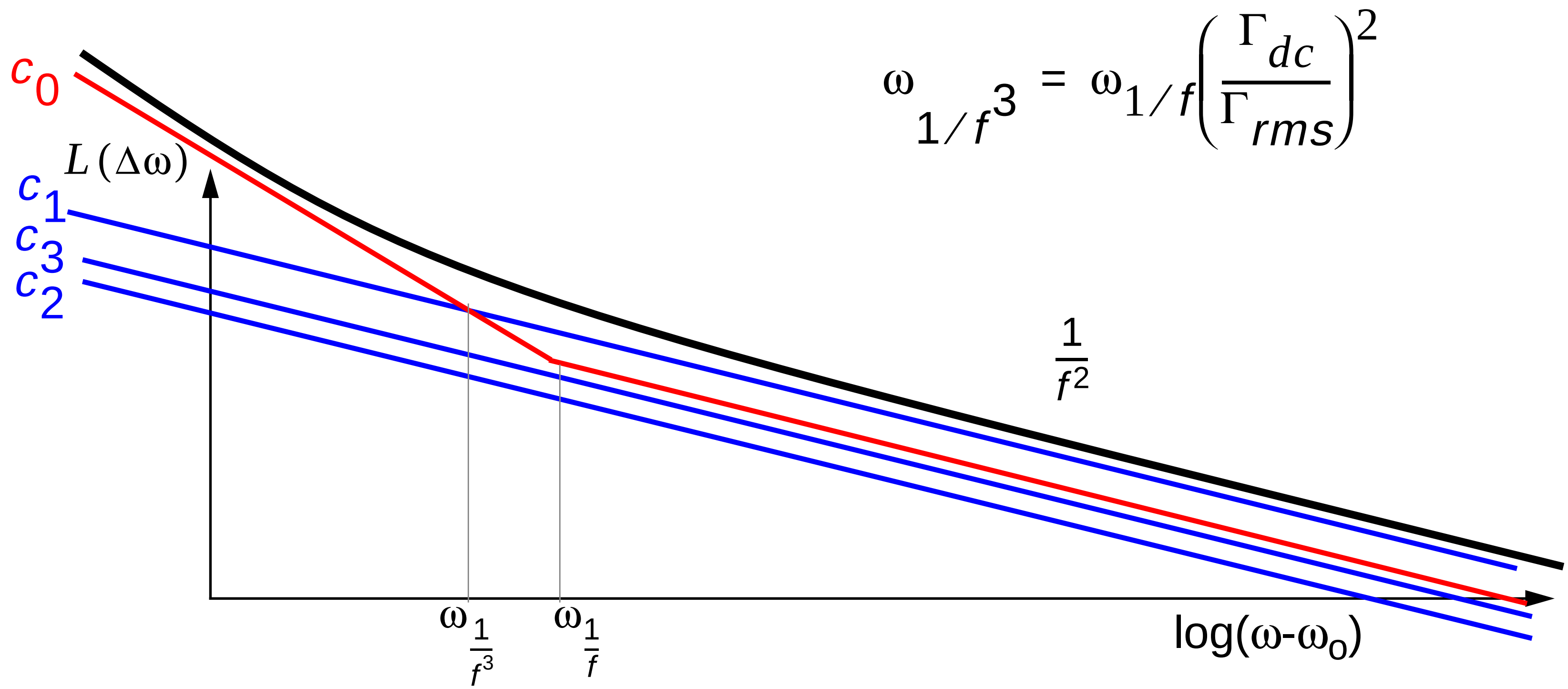
Noise Contributions from $n\omega_o$

$$\phi(t) = \frac{1}{q_{max}}\left[c_0 \int_{-\infty}^{t} i(\tau)d\tau + \sum_{n=1}^{\infty} c_n \int_{-\infty}^{t} i(\tau)\cos(n\omega\tau)d\tau\right]$$



$1/f^3$ Corner of Phase Noise Spectrum

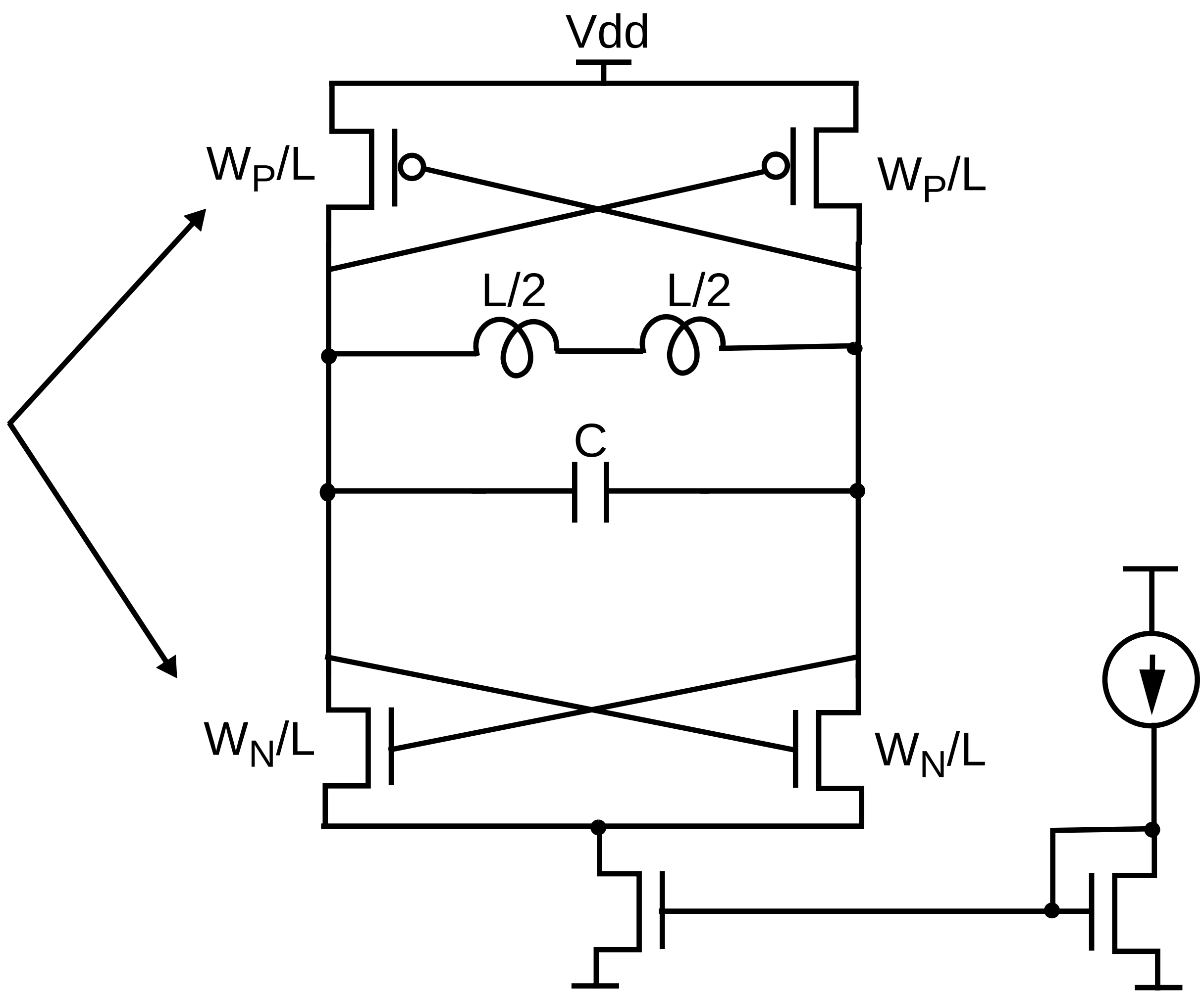
The $1/f^3$ corner of phase noise is NOT the same as the 1/f corner of device noise



By designing for a symmetric waveform, the performance degradation due to low frequency noise can be minimized.

A Symmetric LC Oscillator

Adjust ratios to fine tune symmetry



Uses the same current twice for high transconductance.

[Also appears in: J.Craninckx, *et al*, Proceedings of CICC 97.]

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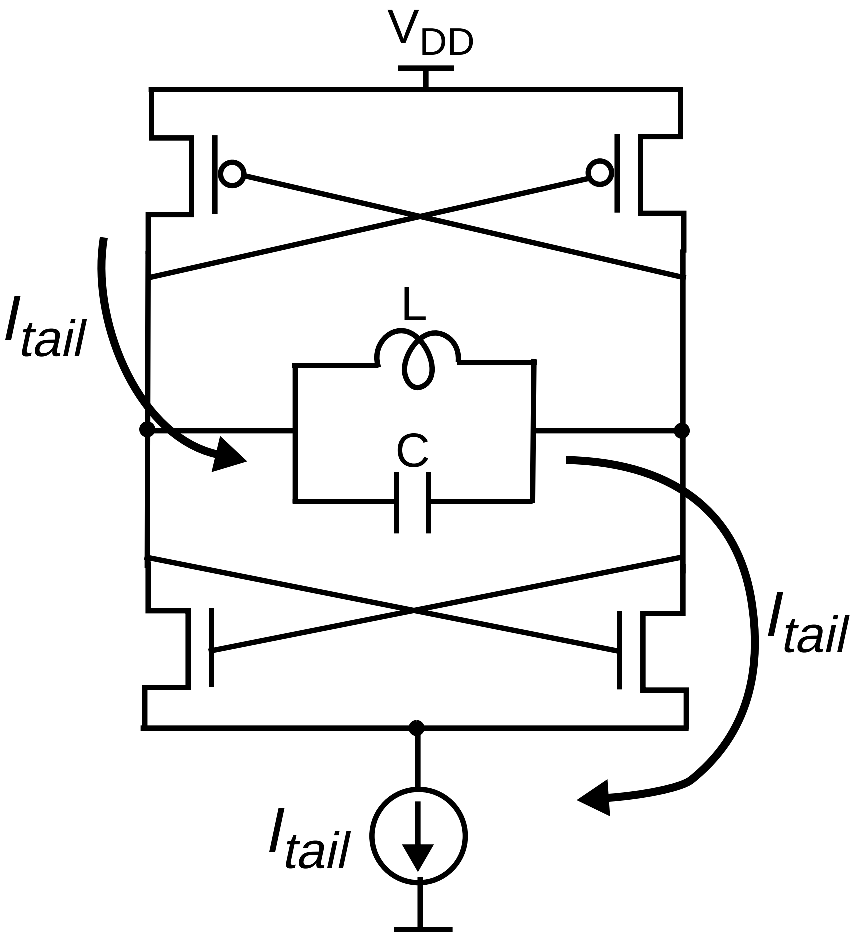
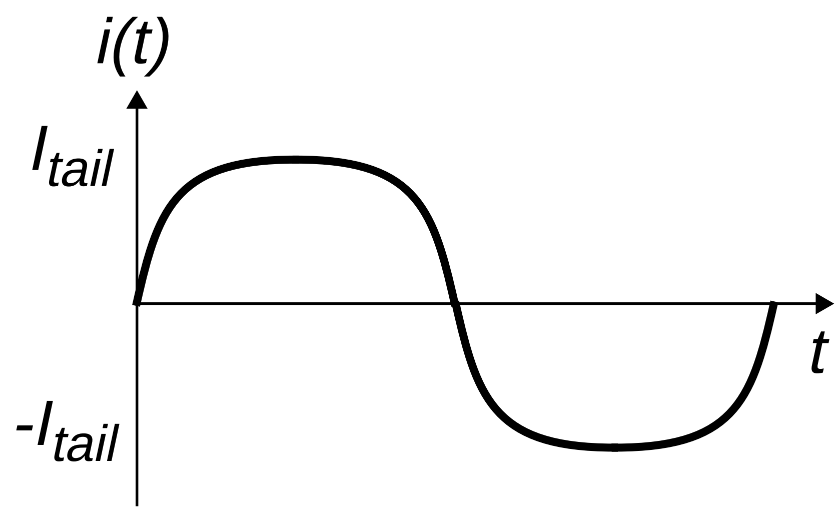
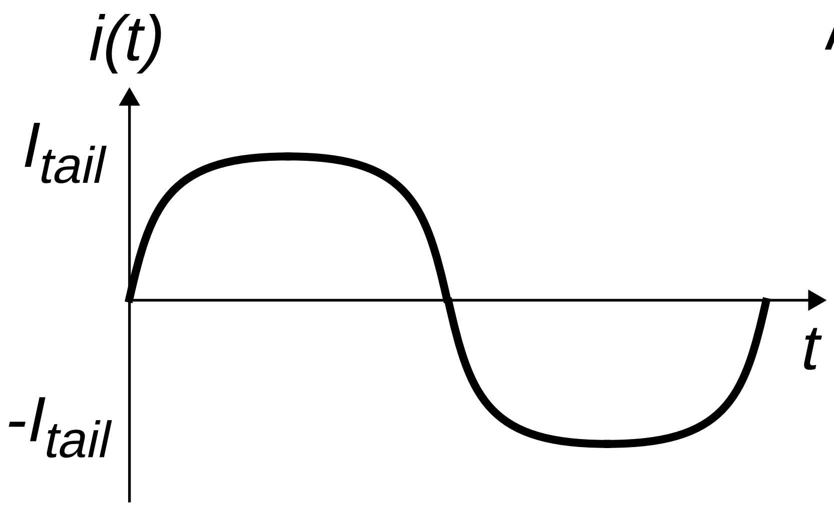
Tank Voltage Amplitude



Assuming fast switching of the differential pair, the current can be approximated as:



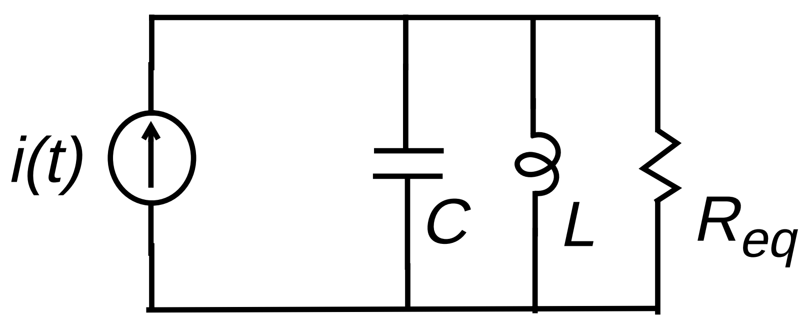
Tank Voltage Amplitude



Assuming rectangular waveform:

$$V_{max} = \frac{4}{\pi} I_{tail} R_{eq}$$

Effectively, the current waveform is closer to sinusoidal, therefore:

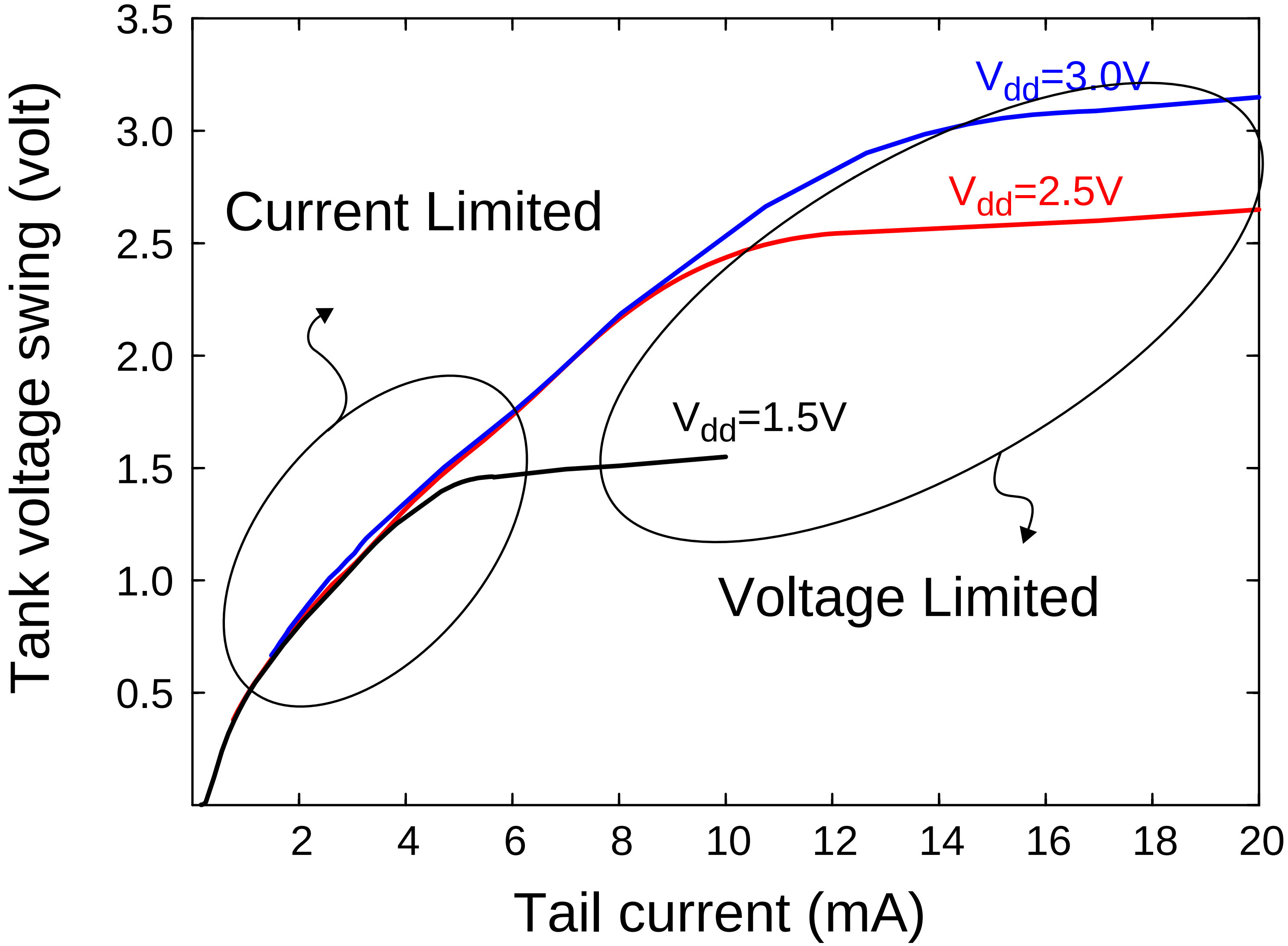


$$V_{max} \approx I_{tail} R_{eq}$$

"Current limited" mode.

Modes of Amplitude Limiting

Complementary cross-coupled LC oscillator



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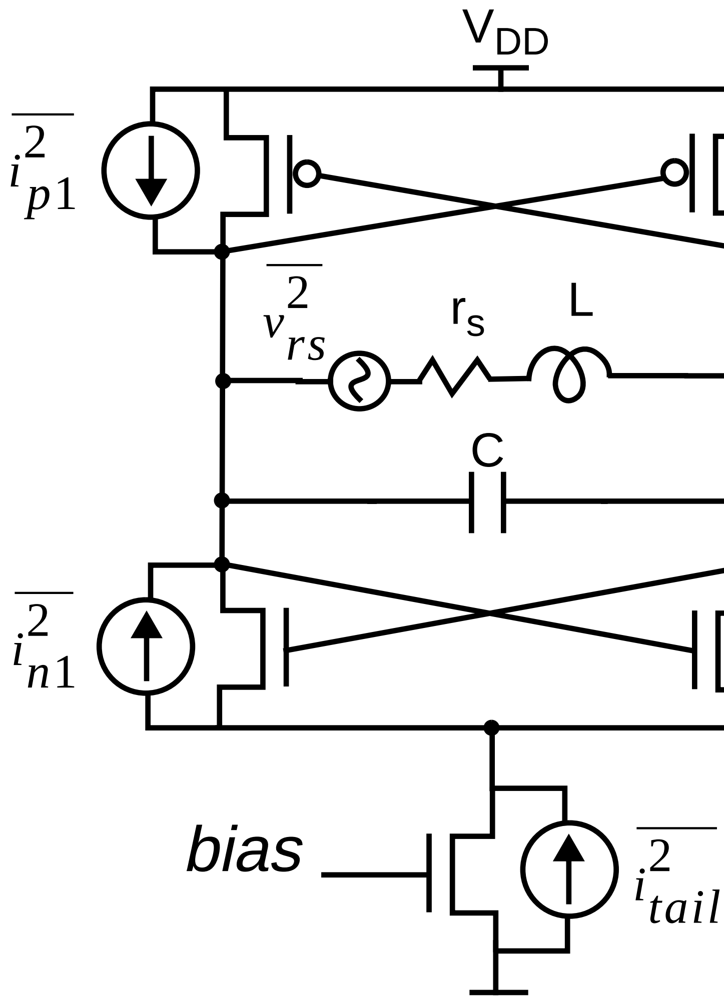
Major Noise Sources



Different noise sources affect phase noise differently.

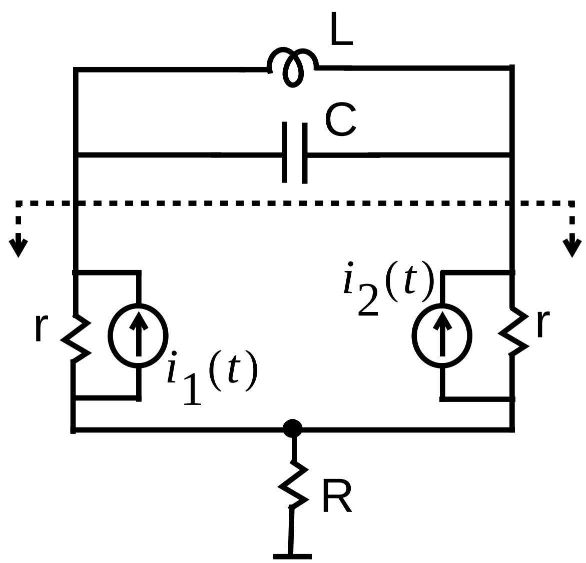
$$\frac{\overline{i_n^2}}{\Delta f} = 4kT\gamma\mu C_{ox}\frac{W}{L}(V_{GS}-V_T)$$

Valid in both long and short channel regimes.

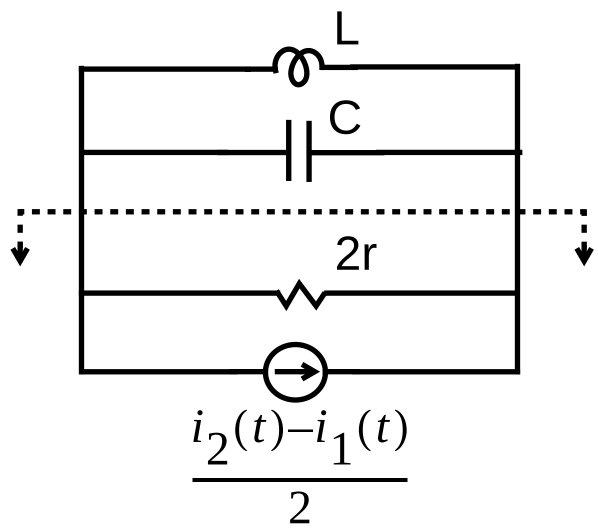
Inductor Noise:

$$\frac{\overline{v_n^2}}{\Delta f} = 4kTr_s$$

Equivalent Circuit for Differential Sources



Differential Equivalent



$$\left.\frac{\overline{i_n^2}}{\Delta f}\right|_{diff-pair} = \frac{1}{4}\left(\frac{\overline{i_{n1}^2}}{\Delta f}+\frac{\overline{i_{n2}^2}}{\Delta f}+\frac{\overline{i_{p1}^2}}{\Delta f}+\frac{\overline{i_{p2}^2}}{\Delta f}\right) = \frac{1}{2}\left(\frac{\overline{i_n^2}}{\Delta f}+\frac{\overline{i_p^2}}{\Delta f}\right)$$

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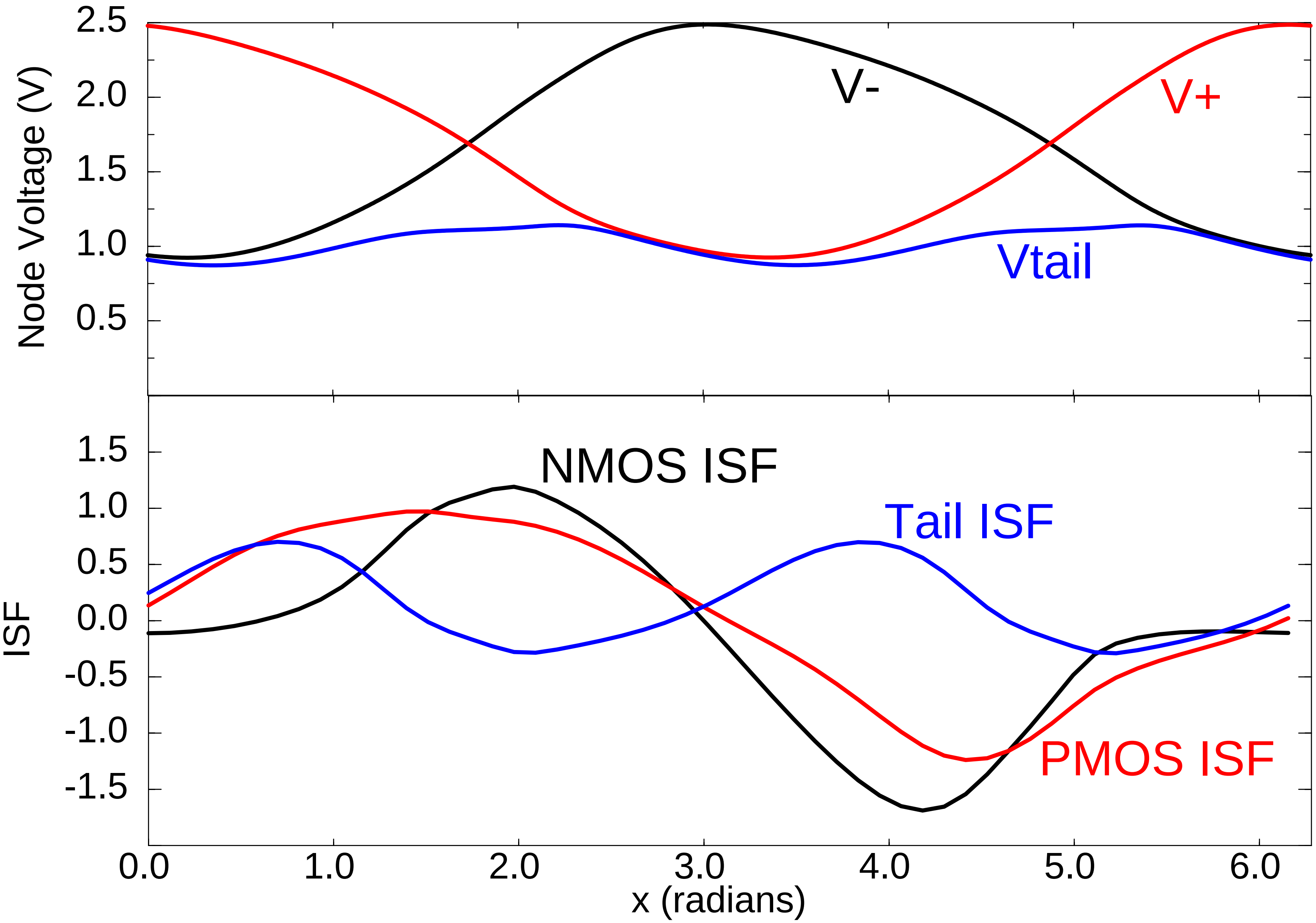
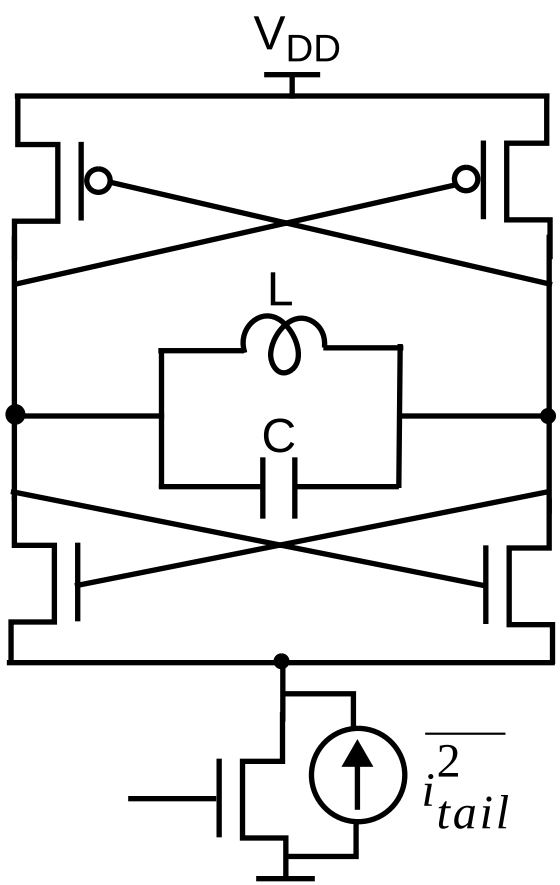
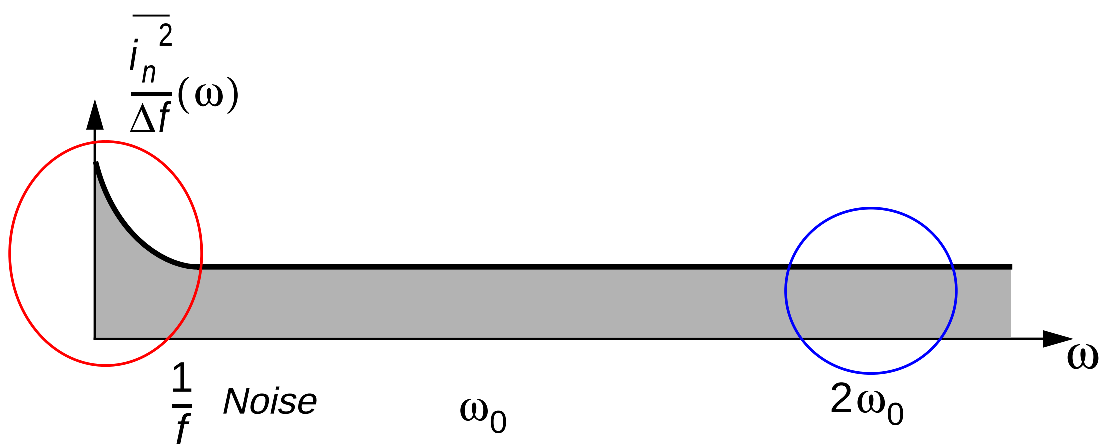
Waveform and ISF



Effect of Tail Current Source



For the tail current source, only low frequency noise and noise in the vicinity of even harmonics of the tail current source affect phase noise.



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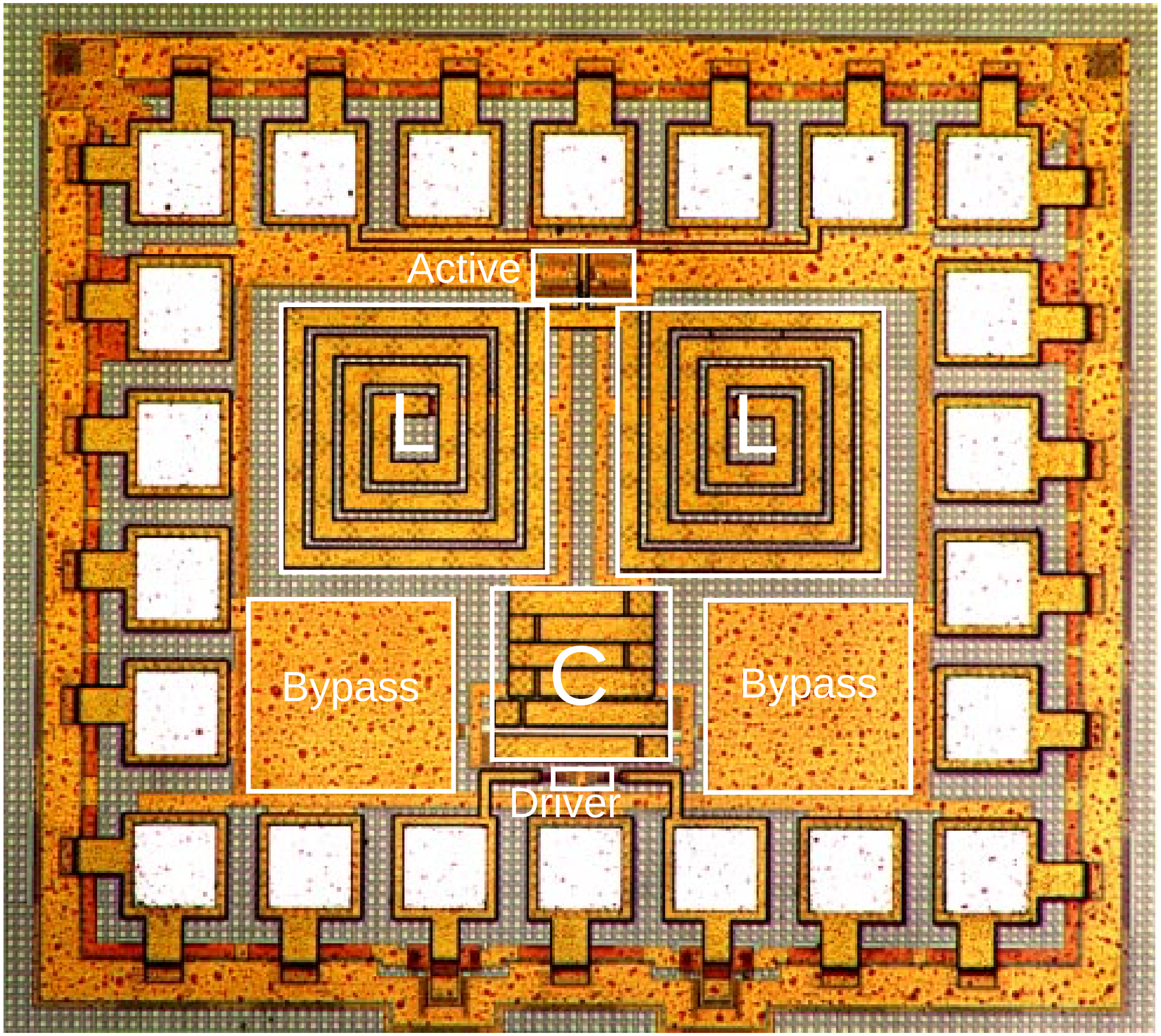
Die Photo of the Complementary Oscillator

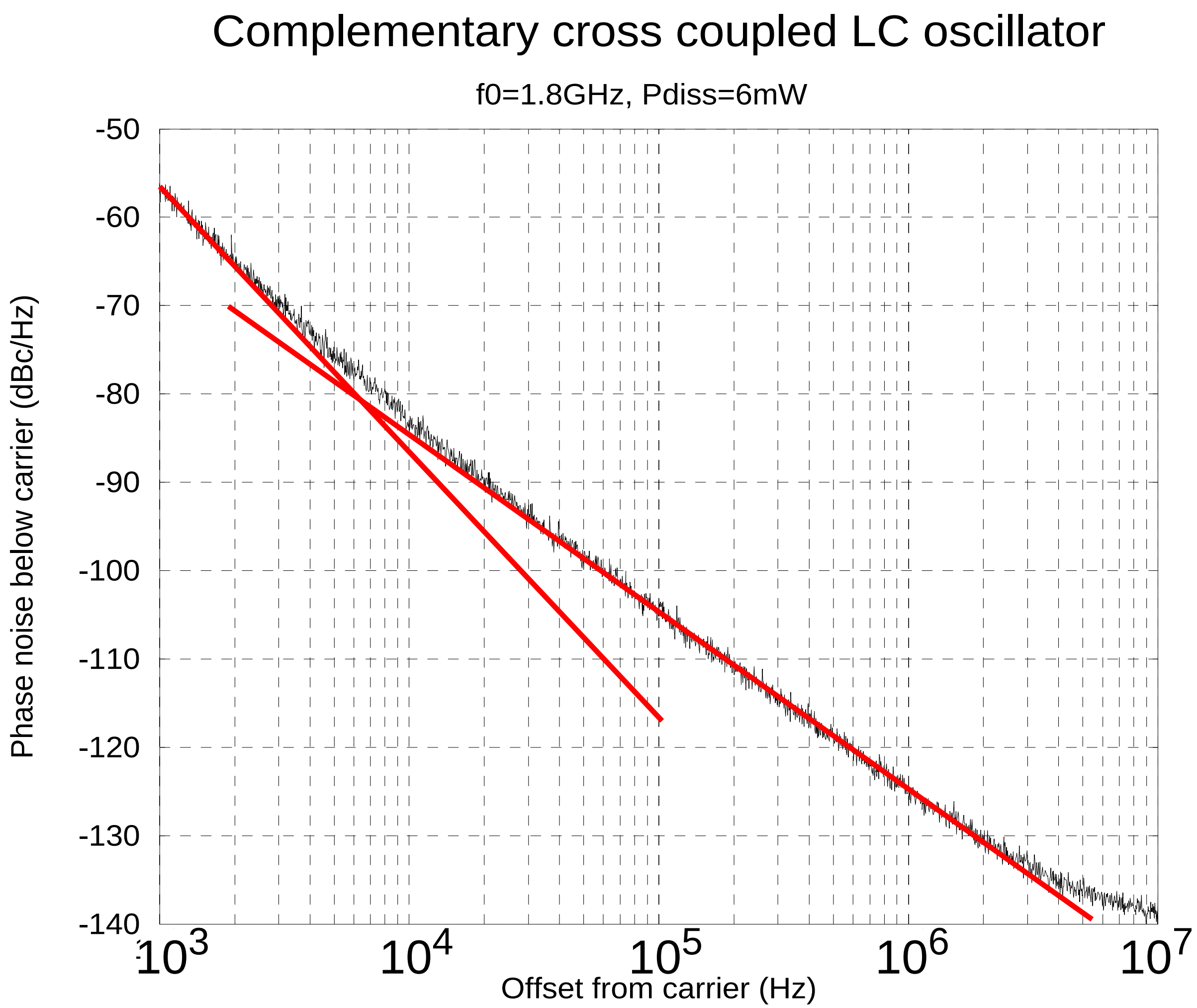


0.25µm process

700µm x 800µm

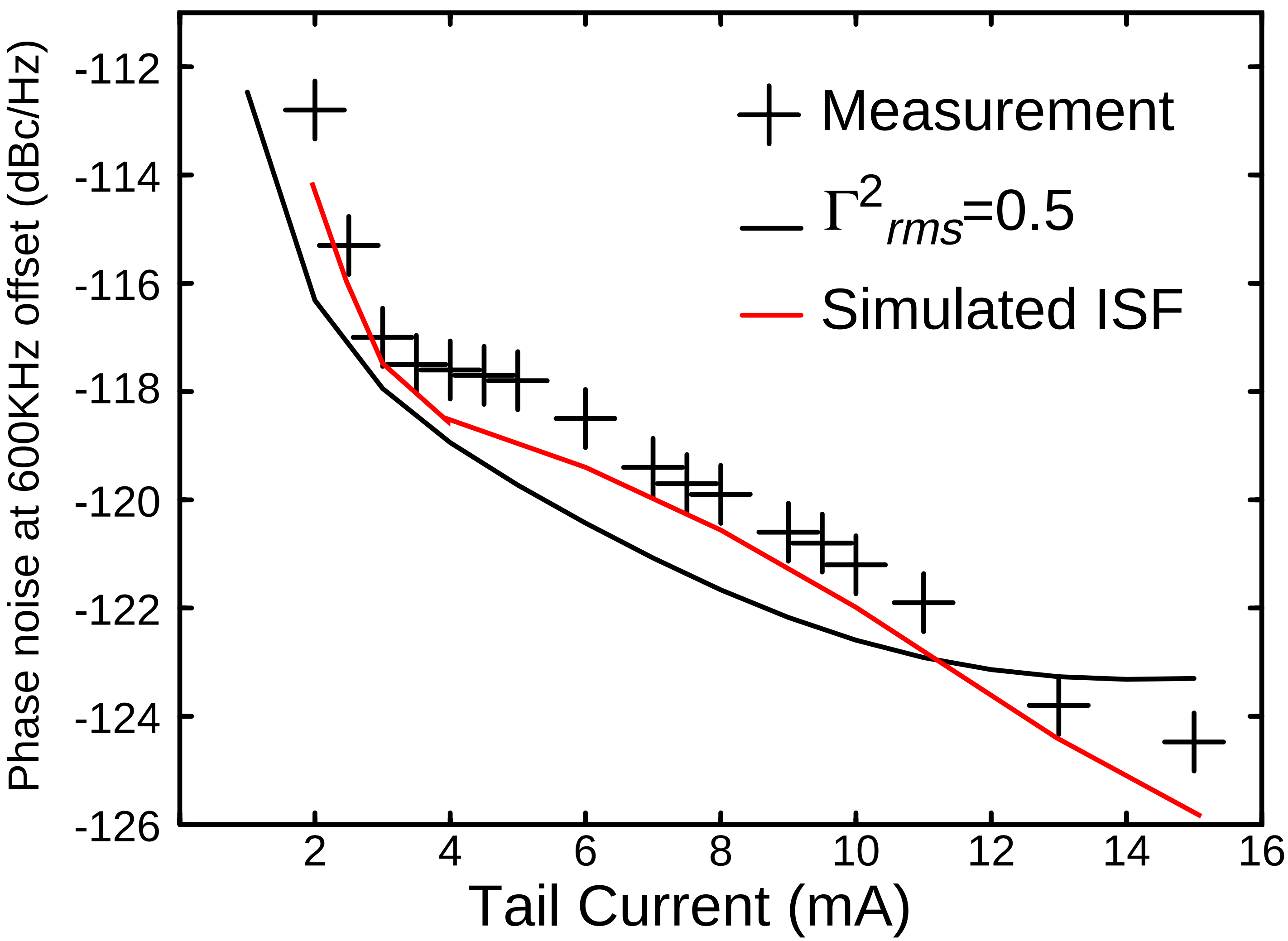
Pad limited

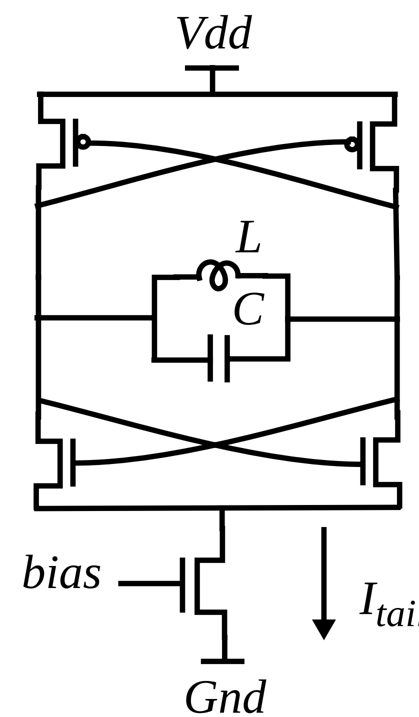
Phase Noise vs. Offset from Carrier



Complementary Cross-Coupled LC Oscillator

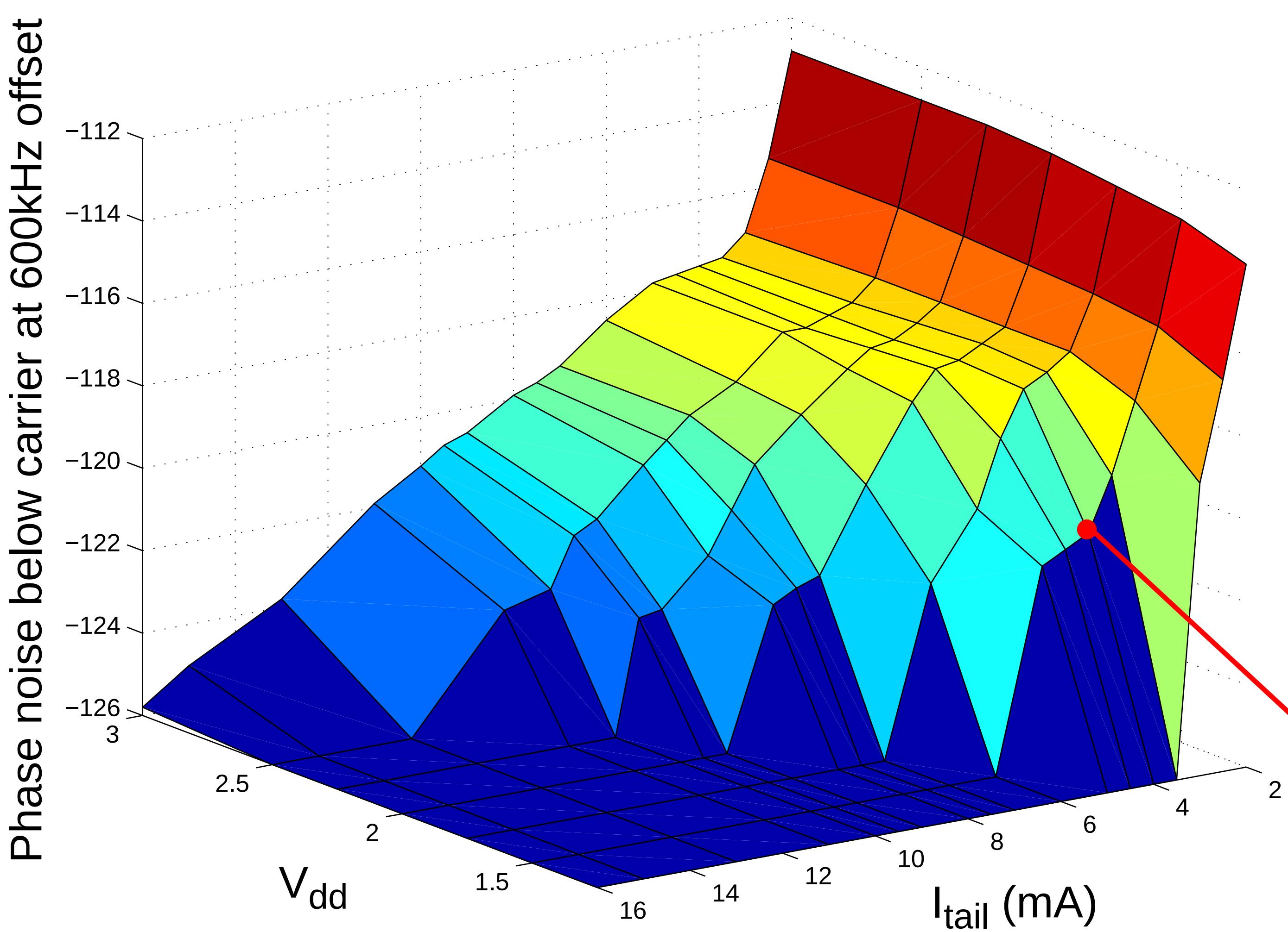
f_0=1.8GHz, 0.25μm Process (V_{DD} =3V)

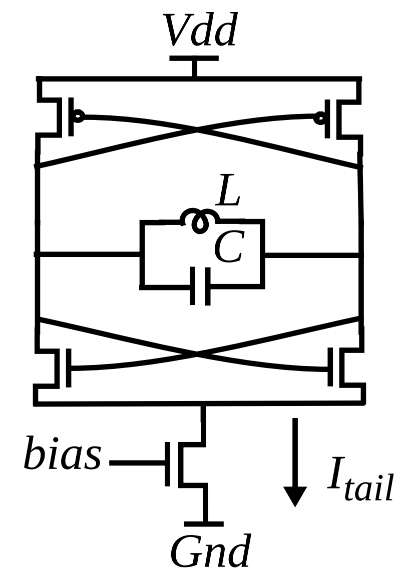




Complementary Cross-Coupled VCO

f_0=1.8GHz, 0.25µm Process

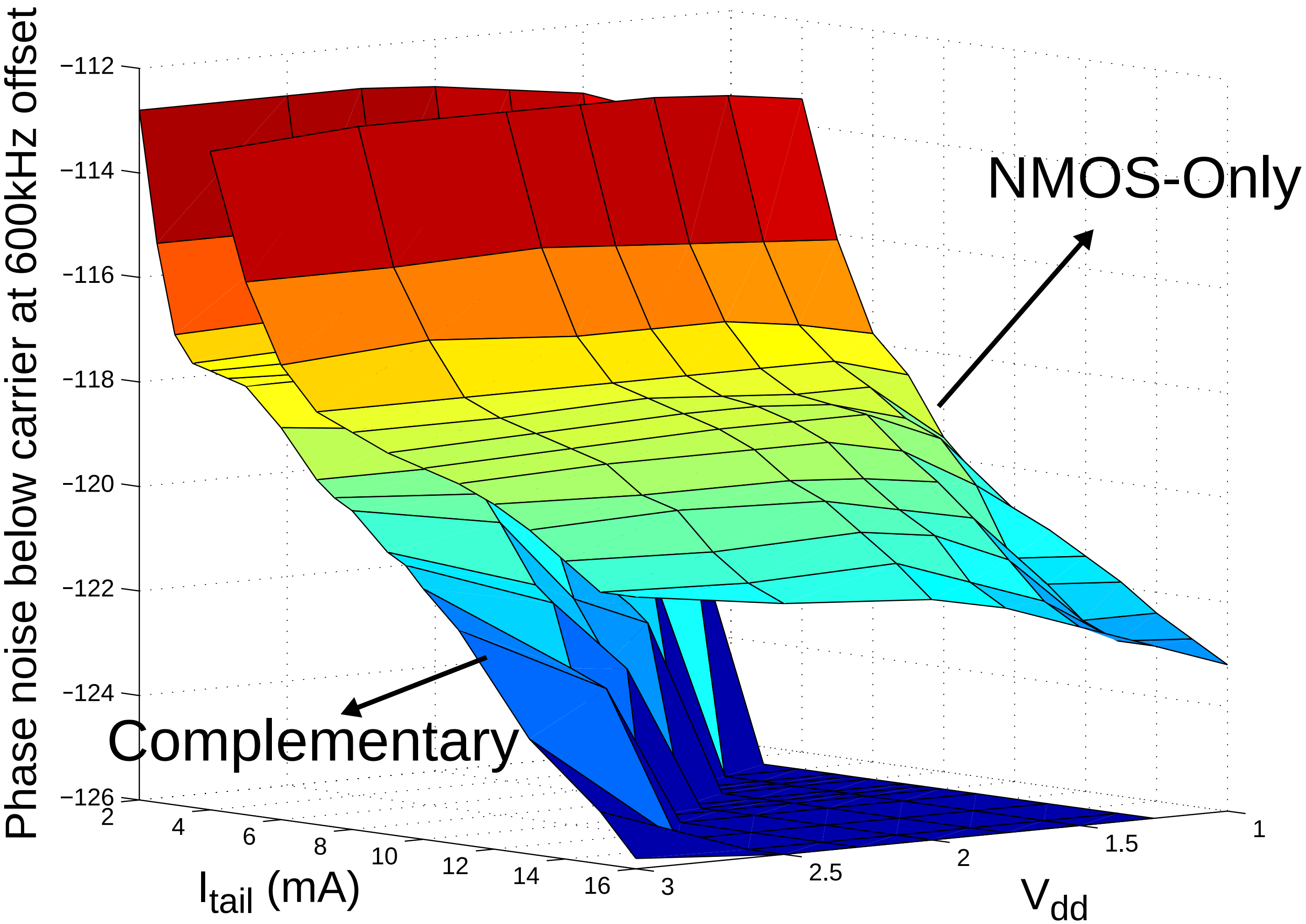


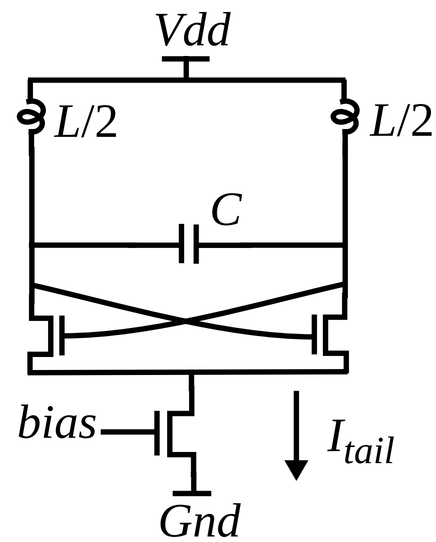


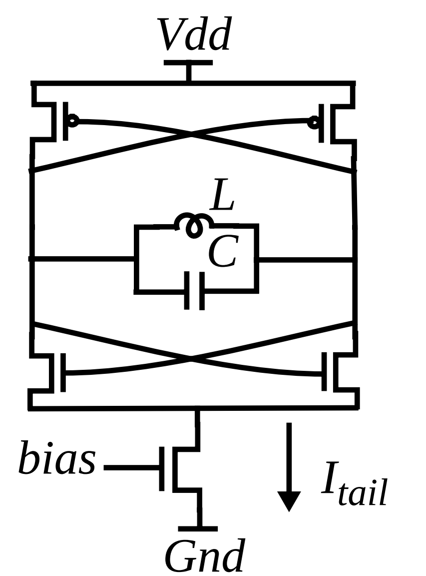
f_0=1.8GHz
P=6mW
-121dBc/Hz@600kHz

Complementary vs. NMOS-Only VCO

f_0=1.8GHz, 0.25µm Process







Conclusion

- Phase noise of differential MOS oscillators is analyzed.
- The effect of tail current source on the amplitude is discussed.
- Major noise sources are identified.
- The effect of tail current source noise is shown.
- Good agreement between theory and measurements is observed.