Ming Hsieh Department of Electrical Engineering

Analysis and Design of Low Phase Noise Oscillators with Nonlinear Resonators

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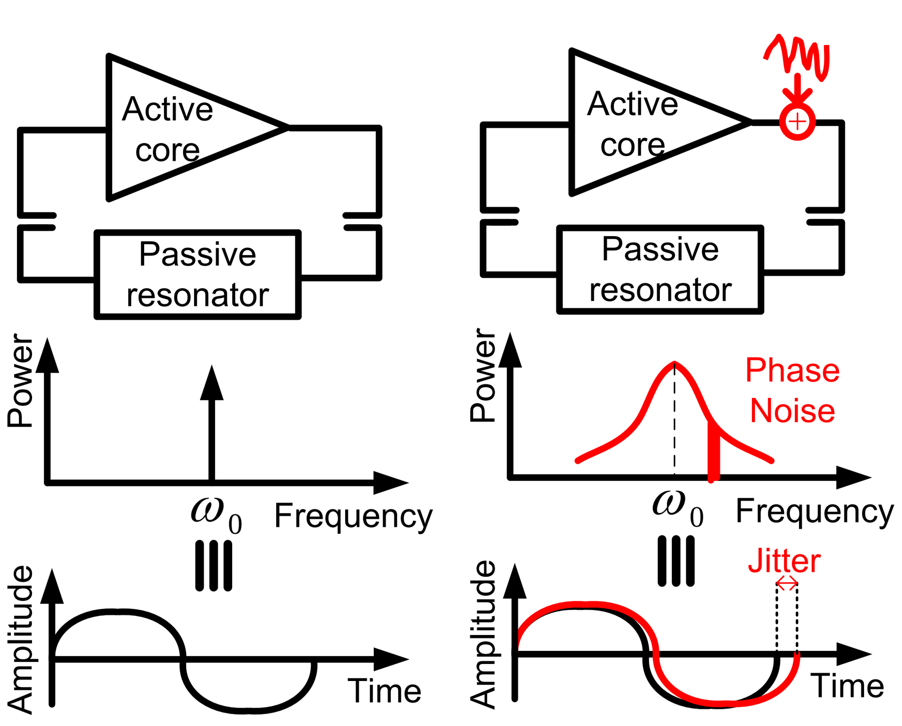
Motivation

Amplitude Noise, Phase Noise and Jitter

Ideal Oscillator | **Real Oscillator** | **Definitions**

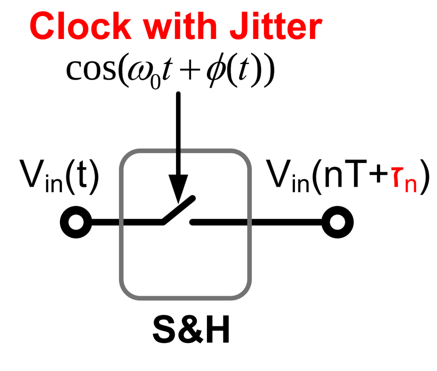


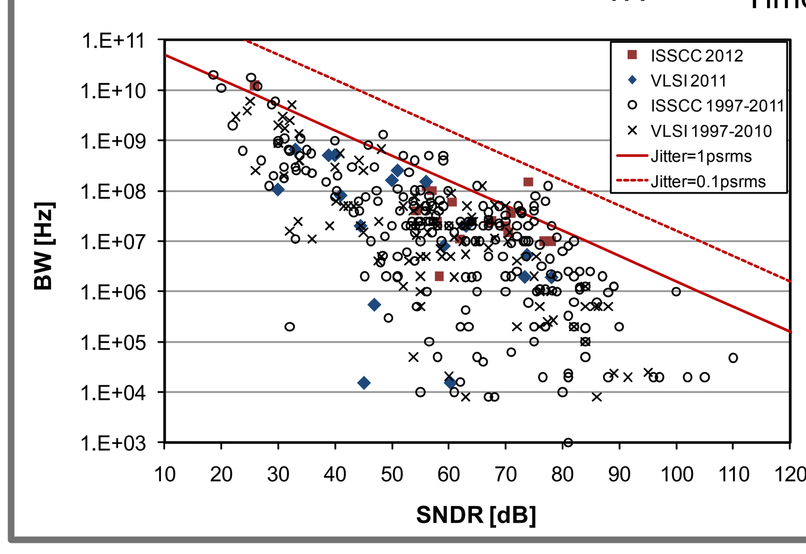
$a\cos(\omega_0 t)$ | $(a + a_n(t))\cos(\omega_0 t + \phi(t))$

AM Noise	PM Noise
$a_n(t)$	$\varphi(t)$
FM Noise	
$\frac{\varphi^{\bullet}(t)}{2\pi}$	
PSD of PM Noise	
$S_\varphi(\Omega)$	
Timing Jitter	
$\frac{\varphi(t)}{\omega_0}$	
Phase Noise	
$l(\Omega) = 10\log\left(\frac{1}{2}S_\varphi(\Omega)\right)$	

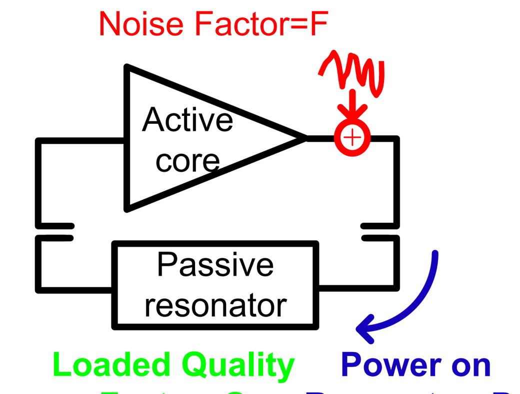
Jitter in Data Conversion

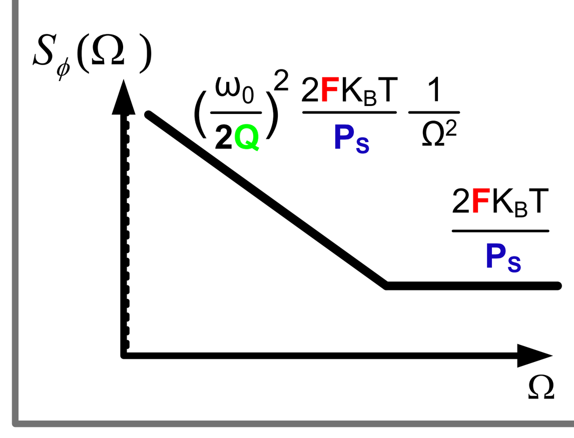
Clock with Jitter $\cos(\omega_0 t + \phi(t))$





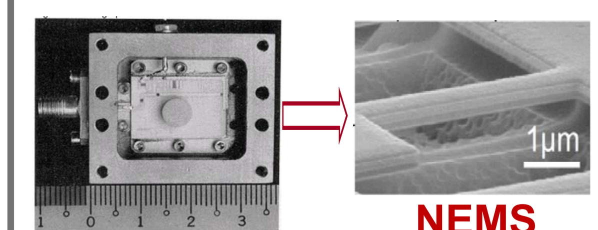
Basic Model





$$\left(\frac{\omega_0}{2Q}\right)^2 \frac{2FK_BT}{P_S}\frac{1}{\Omega^2}$$

Miniaturization



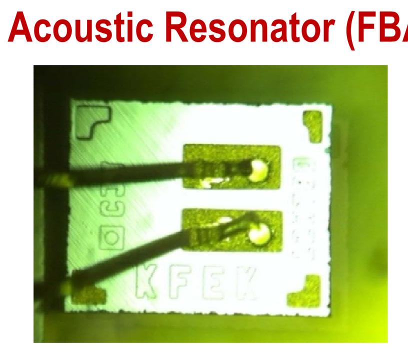
DRO | NEMS Resonator

- Complex systems in small form factors
- Power reduction due to lower weight (e.g., space applications)
- Lower quality factor of resonator
- Smaller resonator power handling (e.g., nonlinear behavior at larger power levels)

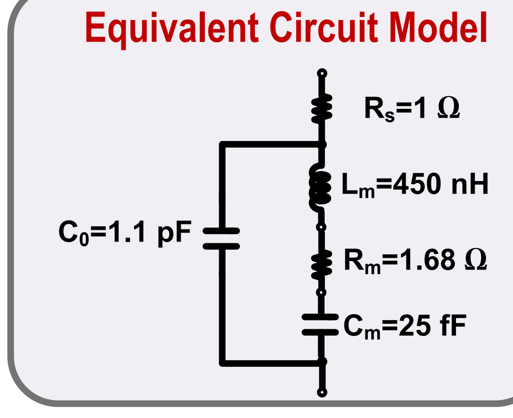
Oscillator Noise analysis with Linear Resonator

Linear Resonator Model

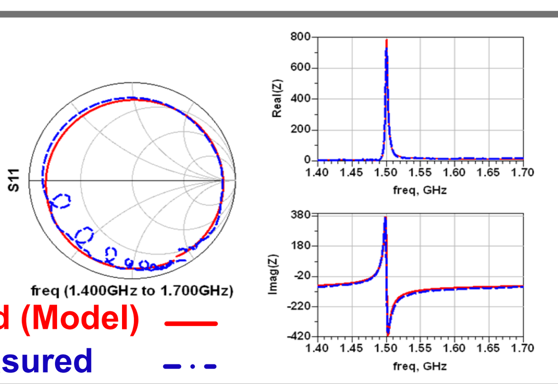
AlN Piezoelectric Thin Film Bulk Acoustic Resonator (FBAR)



Equivalent Circuit Model

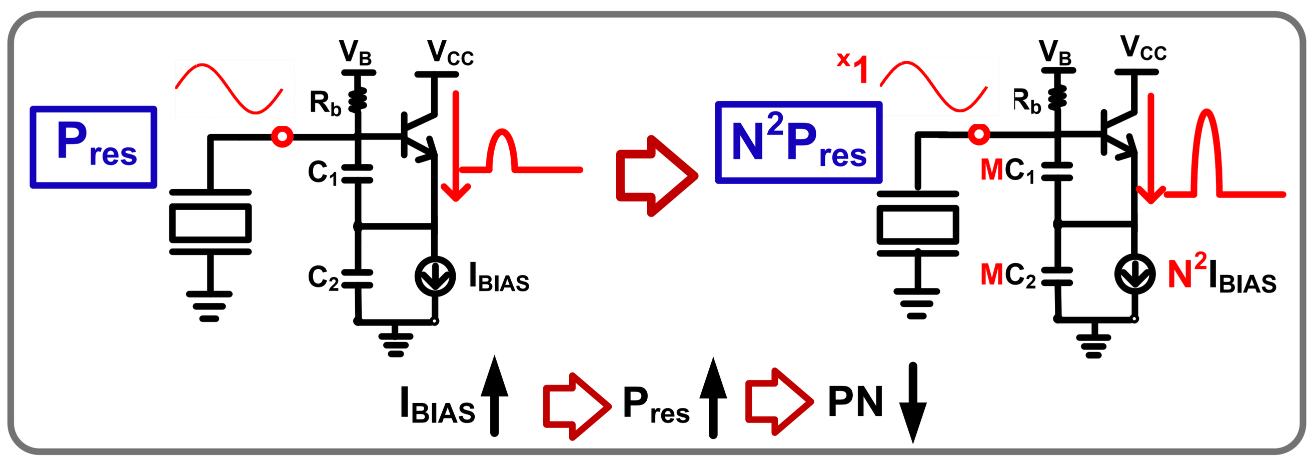


Small-Signal S-parameter Measurement and Modeling



Simulated (Model) —
Measured - - -

Noise Analysis and Power scaling

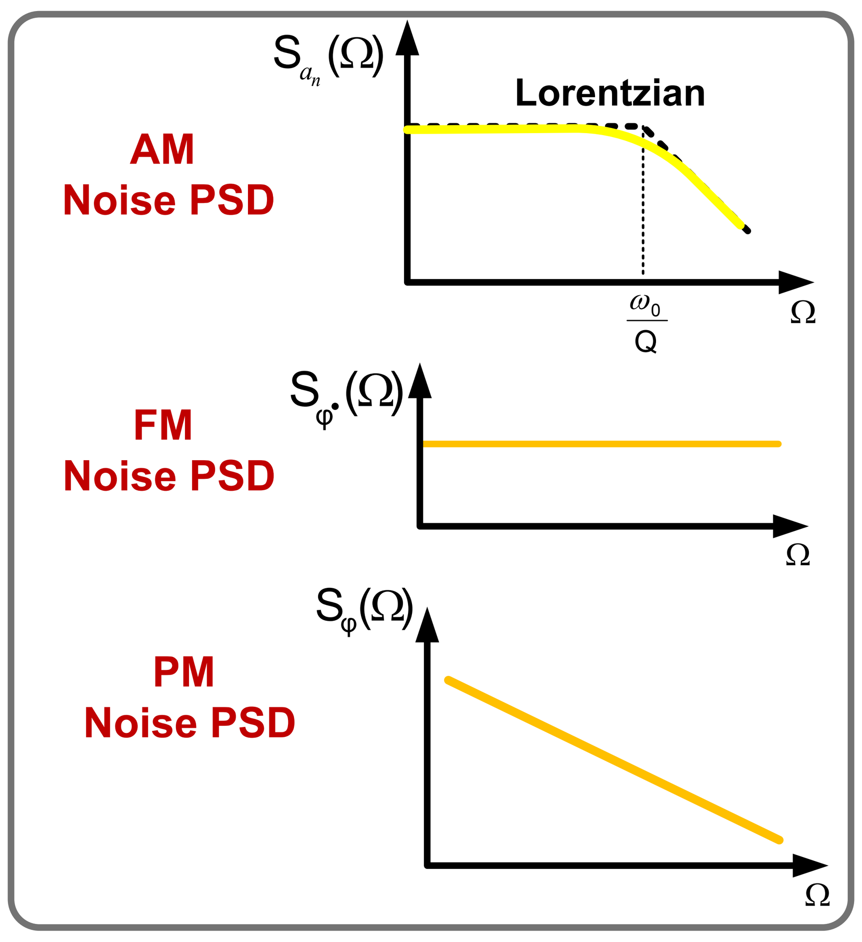


AM Noise SDE $a^{\bullet}(t) = f(a(t), I_{BIAS}) + \frac{I_n(t)}{\lambda C_2}\cos(\omega_0 t + \phi(t))$

Deterministic Term | Stochastic Term

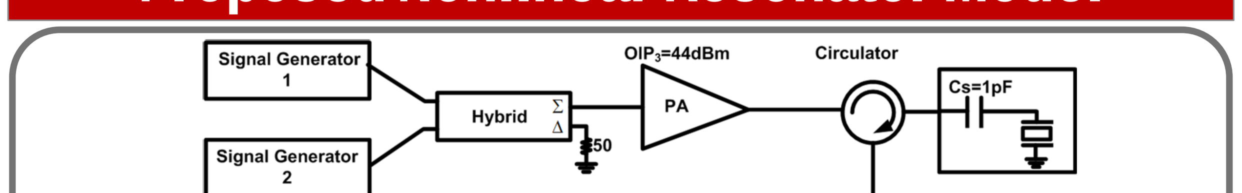
PM Noise SDE $\phi^{\bullet}(t) = \frac{I_n(t)}{\lambda C_2 a(t)}\sin(\omega_0 t + \phi(t))$

Standard Diffusion Process

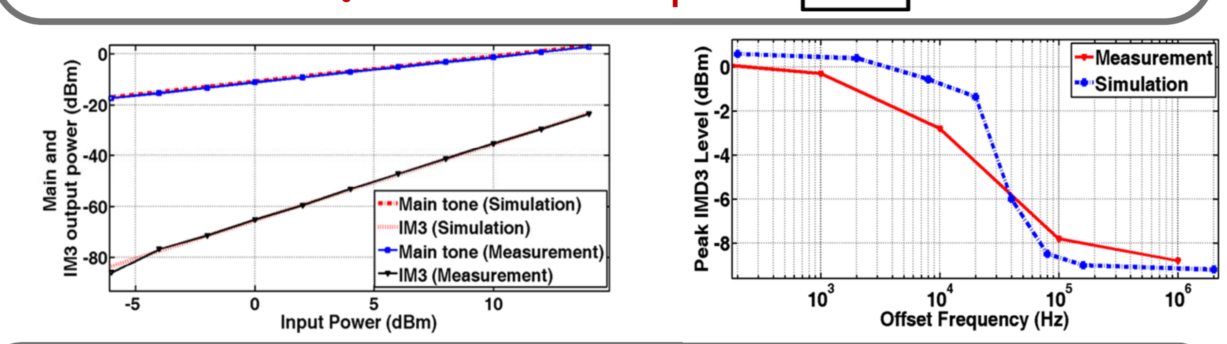


Oscillator Noise Analysis with Nonlinear Resonator

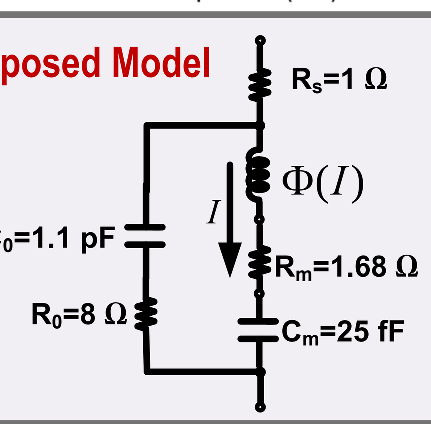
Proposed Nonlinear Resonator Model



2-tone IMD₃ Measurement Setup



Proposed Model



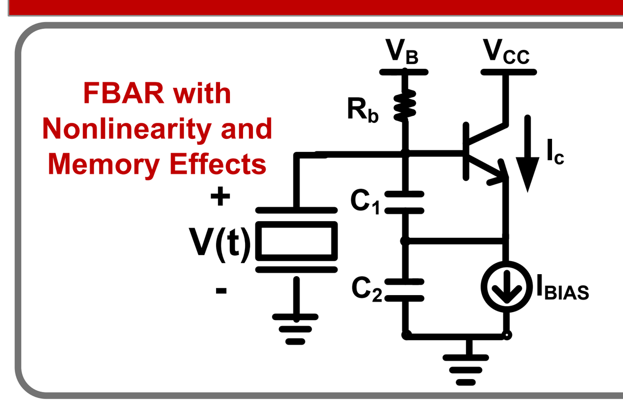
$$L(h(t)) = \frac{s\frac{\omega_0}{Q_{NL}}}{s^2 + s\frac{\omega_0}{Q_{NL}} + \omega_0^2}$$

$$\Phi(I) = 450nH.(I + 0.05I^3 + .15(I*h)^2 I)$$

$$Q_{NL} = 37500$$

Nonlinearity | Memory

Noise Analysis



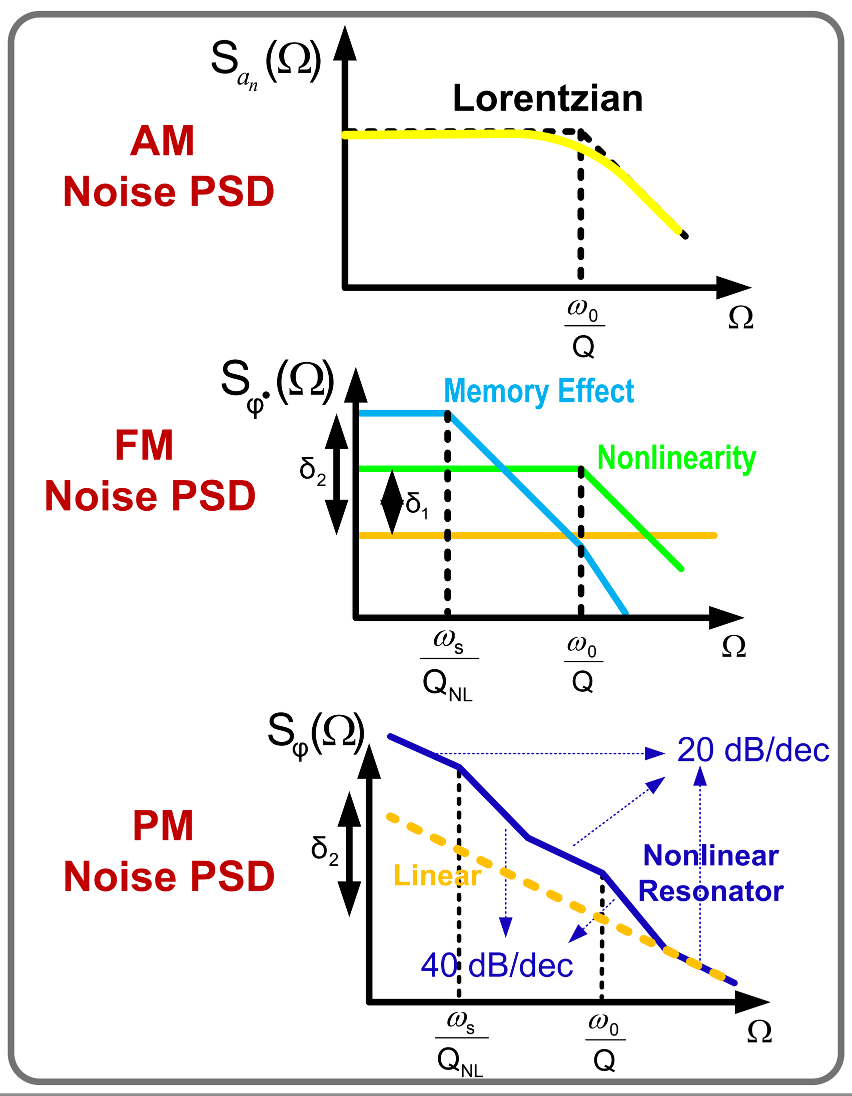
$$V(t) = a(t)\cos(\omega_0 t + \phi(t))$$

$$a^{\bullet}(t) = f(a(t), I_{BIAS}) + \frac{I_n(t)}{\lambda C_2}\cos(\omega_0 t + \phi(t))$$

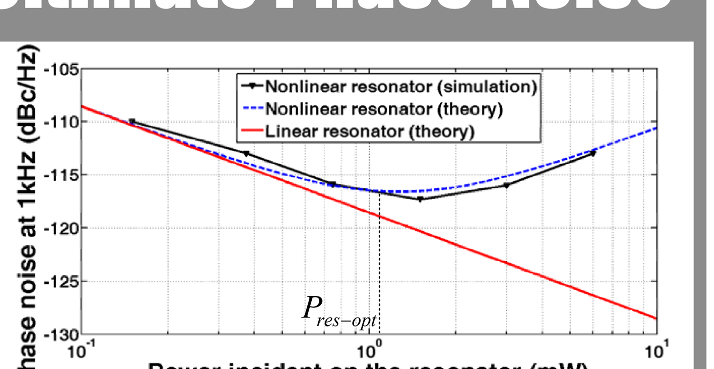
$$\phi^{\bullet}(t) = \frac{I_n(t)}{\lambda C_2 a(t)}\sin(\omega_0 t + \phi(t)) - N_1\Delta L_1 a(t)^2 - N_2\Delta L_2 a_{LP}(t)^2$$

Standard diffusion process | Nonlinearity | Memory Effect

- Use quasi-harmonic approximations and averaging to form SDEs
- Use properties of Ito stochastic integrals to solve the SDEs



Ultimate Phase Noise

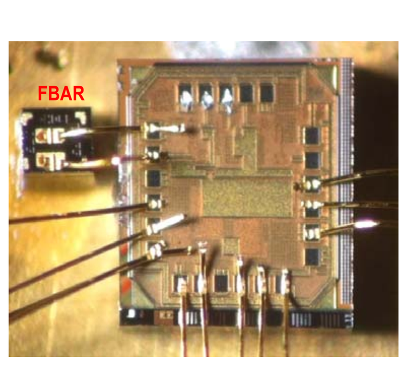


$$P_{res-opt} = \frac{R_m}{3Q_{res}(\Delta L_1 + \Delta L_2)}$$

Ultimate Phase Noise Only function of resonator

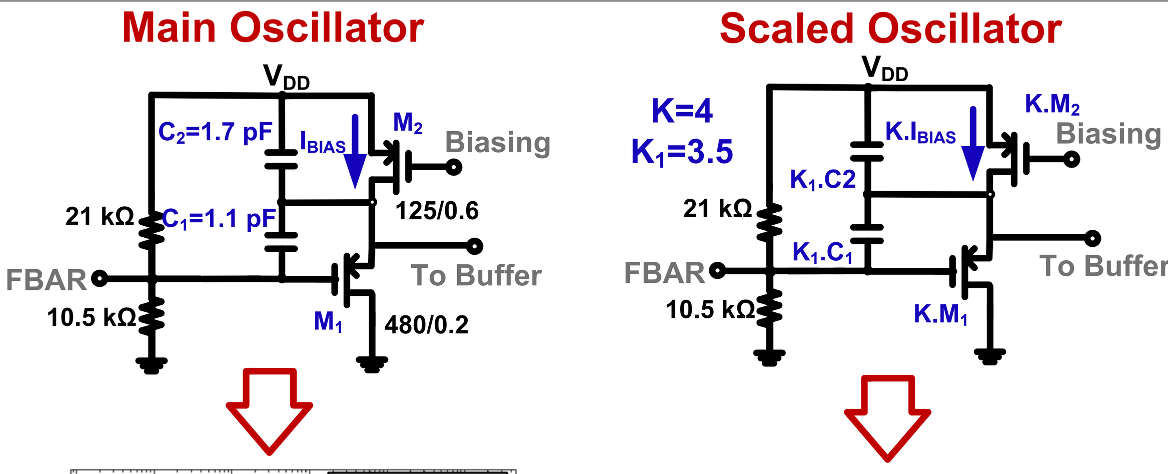
Impementation

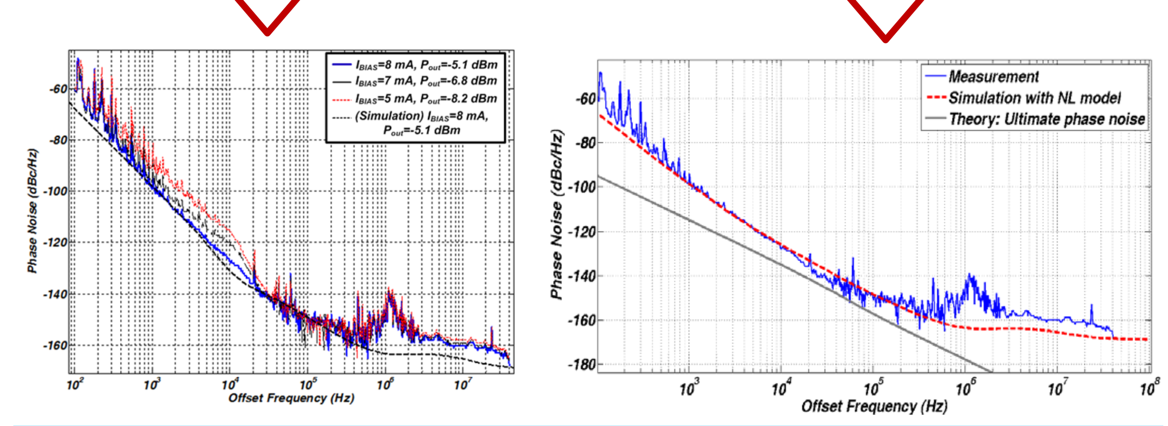
- 1.5 GHz FBAR
- 130 nm CMOS
- Chip area= 1mm²



Schematics and Measurements

Main Oscillator | **Scaled Oscillator**





- Diverge from typical oscillator phase noise profile
- Approaching the phase noise limit of FBAR
- RMS absolute phase jitter=9.8 fs

Comparison Table

	Resonator	Frequency (GHz)	PN @ 1 kHz	PN @ 10 kHz	PN @ 100 kHz	PN @ 10 MHz	Jitter (fs)	Power (mW)
This Work	FBAR (Q_{series} = 1500)	1.5	-100	-125	-145	-160	9.8	40 (w/ buffer)
Elec. Dev. Letter. 2008	FBAR (Q_{series} = 1000)	0.6	-100	-130	-149	-152	40	5.3 (w/o buffer)
TMTT 2008	Air Dielectric Cavity (Q = 200,000)	10	-160	-170	-	-	-	Output Power= 28 dBm
Vectron.com	SAW (Q = 9800)	1.97	-90	-118	-139	-158	14	780

Conclusion & Future Work

- Model nonlinearity and memory effect of miniature resonators
- Analysis of oscillators with NL resonators
- 1.5 GHz FBAR oscillator with 9.8 fs jitter

- Exploit nonlinearity to enhance oscillator phase noise
- Investigate other miniature resonators' nonlinearity effects

[1] A. Imani, H. Hashemi, "Monolithic low phase-noise CMOS FBAR nonlinear oscillators," GOMACTech, 2012.

[2] A. Imani, H. Hashemi, "Analysis and design of low phase noise oscillators with nonlinear resonators," Submitted to TMTT, 2012.

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