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Motivation

Amplitude and Phase Noise

Ideal Oscillator

Real Oscillator

Amplitude vs Time plots showing a clean sine wave and a noisy sine wave with jitter.

Mathematical models: $a \cos(\omega_0 t)$ and $(a + a_n(t)) \cos(\omega_0 t + \phi(t))$

AM Noise	PM Noise	FM Noise	PSD of PM Noise
$a_n(t)$	$\phi(t)$	$\frac{\dot{\phi}(t)}{2\pi}$	$S_\phi(\Omega)$

Phase Noise: $L(\Omega) = 10 \log\left(\frac{1}{2} S_\phi(\Omega)\right)$

Stable Frequency Generation

Sapphire-Loaded Cavity Resonator

D. Green, *IFCS '2006*

Low-Loss Optical Fiber

L. Maleki, *IFCS '2003*

High Quality factor (Q) resonators or low-loss delay elements, crucial for stable oscillators. Couple from low loss medium to electrical domain

Miniaturization of Resonators

DRO vs **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)

Resonator Used in This Work

AlN Piezoelectric Thin Film Bulk Acoustic Resonator (FBAR)

Equivalent Circuit Model

$R_s=1 \Omega$
 $L_m=450 \text{ nH}$
 $R_m=1.68 \Omega$
 $C_0=1.1 \text{ pF}$
 $C_m=25 \text{ fF}$

Frequency/Phase Discriminator Design

Frequency/Phase Discriminator Basics

$V_{in}(t) = a_o \cos(\omega_o t + \phi(t)) \rightarrow \text{Frequency/Phase Discriminator} \rightarrow V_o(t) = G(t) * \phi(t) + V_{n,out}(t)$

Output Referred Noise

$V_{out}(t) = G(t) * \phi(t)$
 $\text{Gain} = G(\Omega) = \frac{V_{out}(\Omega)}{\phi(\Delta\omega)}$
 $PN_{Floor} = \frac{V_{n,out}(\Omega)}{G(\Omega)}$

To maximize sensitivity (phase noise floor), transfer function magnitude should be maximized when output referred noise is minimized.

Implemented Frequency/Phase Discriminator

$V_{in}(t) = a_o \cos(\omega_o t + \phi(t))$

Notch Filter (FBAR)

Small-input: Low flicker-noise up-conversion

Low Noise Amplifier (LNA)

Phase Shifter

Mixer

Output

$G(\Omega) = a_o A_{LNA} A_{Mixer} \frac{\tau \cdot j\Omega}{\tau \cdot j\Omega + 1}$
 $\tau = \frac{2Q_L}{\omega_o}$

Use notch filter to suppress the carrier $\rightarrow$ Low flicker noise up-conversion in LNA
Larger $Q_L \rightarrow$ Higher sensitivity

1.8x3 mm² 0.13 μm CMOS
Power = 26 mW.

Notch Filter

FBAR

VCO

$R_0=10 \text{ k}\Omega$

$C_s=1 \text{ pF}$

Linearized Voltage Controlled Resistor

$R_p=35 \Omega$

$C_R=12.8 \text{ pF}$

$L=435 \text{ pH}$

$C_0=1.7 \text{ pF}$

$M_s=7 \Omega$

$R_s=280/0.4$

$R_L=600 \Omega$

Depth Control

Group Delay=130 ns

Voltage controlled resistor balances the loss.

Frequency/Phase Discriminator Sensitivity Measurements

Discriminator Transfer Gain

Measured (quadrature)

Simulated (quadrature)

Frequency discriminator

Phase discriminator

Slope= $a_o A_{LNA} A_{Mixer} \tau$

Acts as frequency discriminator at low offset frequencies.
Acts as phase discriminator at high offset frequencies.
Gain reduces when frequency is off from notch frequency.

Cross-Spectrum Noise Measurement

Signal Generator

3dB Splitter

Frequency / Phase Discriminator 1

Frequency / Phase Discriminator 2

Back-end amplification and filtering

ADC

Spectrum analysis

$x(t) = a_x(t) + C_x(t)$

$y(t) = b_y(t) + C_y(t)$

Signal Generator Discriminated phase noise $C_n(t) = G(t) * \phi_{SG}(t)$

Inherent Output Noise of Two Discriminators $a_n(t) \perp b_n(t)$

Measured (discriminator 1)

Measured (discriminator 2)

Measured (cross-spectrum, averaging=1000)

Measured (at 2 kHz off, subtracted spectrum)

Measured (at quadrature, subtracted spectrum)

Simulated output noise

Feedback-Feedforward Phase Noise Cancellation

Phase Shifter (I)

Amplitude Loop Filter

Mixer (I)

Phase Shifter (Q)

Mixer (Q)

Phase Modulator

FF Filter

Output Buffer

indio

Feed-back Phase Noise Cancellation

Feed-forward Phase Noise Cancellation

Simulation (FB-Only)

Measurement (FB-Only)

Measurement (open loop)

Simulation (open loop)

Discriminator PN floor

Comparison Table

	Resonator	Frequency (GHz)	PN @ 1 kHz	PN @ 10 kHz	PN @ 100 kHz	PN @ 1 MHz	PN @ 4 MHz	Power (mW)
Freq./phase Disc.	FBAR $Q_{series}=1500$	1.5	-	-122	-142	-162	-165.5	26
PN cancellation	FBAR $Q_{series}=1500$	1.5	-90	-120	-137	-141	-136	350
Elec. Dev. Letter. 2008	FBAR $Q_{series}=1500$	0.6	-100	-130	-149	-152	-152	5.3 (w/o buffer)
TMTT 2008	Air dielectric cavity $Q=200000$	10	-160	-170	-	-	-	Output power=28 dBm
[2]	FBAR $Q_{series}=1500$	1.5	-100	-125	-145	-145	-160	40

Conclusions

Integrated implementation of low phase noise floor frequency/phase discriminator.

Techniques to prevent low-frequency noise up-conversion.

Propose a phase noise cancellation scheme reaching the discriminator phase noise floor.

[1] A. Imani, H. Hashemi, "A low-noise FBAR-CMOS frequency/phase discriminator for phase noise measurement and cancellation," Submitted to RFIC 2013.

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