“Comparison and Status of Low-noise X-band Oscillator and Amplifier Technologies”

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Collaborations with Army Research Lab, Office of Naval Research, Optical Frequency Measurements and Ion Storage (NIST), Mayo Foundation, MIT-LL

Acknowledgements of OEWaves, Inc., Poseidon Scientific, Q-Dot, Corp.
Best-in-class PM noise results and descriptions of X-band amplifiers and oscillators based on recent measurements at NIST. Results are at an operating frequency of 10 GHz.

Amplifier PM-noise measurements of:
- SiGe with feedback noise suppression (FBA)
- Commercial amplifiers with feedforward noise suppression (FFA)
- Array of commercial amplifiers with uncorrelated noise
- Typical commercially available amplifiers

Impact of amplifier feedback noise on oscillator, review of Leeson’s model

Oscillator PM-noise measurements of:
- Typical low-noise quartz oscillator, multiplied to 10 GHz
- Optical Electronic Oscillator using fiber-delay-line resonator
- Sapphire-loaded CSO using interferometric carrier suppression
- High-power air-dielectric CSO using 2W drive and impedance controlled carrier suppression
- DRO feedback oscillator
- Optical femtosecond-comb divider with calcium-stabilized reference oscillator
Origins of oscillator phase noise motivates low-noise amplifier development

Phase stabilization of an oscillator with noise sources and a resonator with loaded $Q$, $Q_L$. 

\[ S_b(f_m) \quad \text{noise-free amp (unity gain)} \]

\[ + \]

\[ S_a(f_m) \quad \text{resonator at } f_o, \text{ with } Q_L \]

\[ S_o(f_m) \]
Low-noise Microwave Amplifier Measurements

GENERAL STRATEGY TO ACHIEVE LOW RESIDUAL PHASE NOISE IN AMPLIFIERS

- Use low 1/f noise devices
  - 1/f noise multiplies up into near carrier noise due to amplifier non-linearities
  - Generally HBTs have smaller low-frequency noise than all classes of FETs

- Use a design technique that achieves highly linear amplifier operation
  Possibilities include:
  - Feedback (requires high \( f_t \))
  - Feedforward (best over a narrow band with careful phase match)
  - Parallel HBTs that are graded for low 1/f noise (power/size cost)
  - Predistortion (adds to device noise)
  - LINC - linear amplification using non-linear components (sampling-rate limited)
MECHANICAL DRAWINGS OF FIRST AND SECOND LOOP MODULES OF HYBRID FEEDFORWARD AMPLIFIER (FFA)
(Each Module Plan Dimensions: ~4” x 3”)

LOOP 1 MODULE

- Provision for Pilot Signal
- External Mechanical Phase Adjust
- PCB for Bias Distribution
- Power Amplifier GaAs MMIC
- RT/duroid 6002 "Frame"
- CuW Carrier Plate
- External Delay Line
- Coupler on 10 mil Alumina

OUTPUT

LOOP 2 MODULE

- FFA Output
- LNA MMIC

Courtesy of Mayo Foundation
Low-noise Microwave Amplifier Measurements

BLOCK DIAGRAM FOR BASIC FEEDFORWARD AMPLIFIER

Input $P_{in}$

Power Amplifier

$\eta_1$

$\tau_1$

$\eta_2$

$\gamma_1$

Carrier Suppression at This Point

$\tau_2$

$\eta_3$

Auxiliary Amplifier

$\gamma_2$

Output

MAY_12 / 2003 / VS / 19057

Courtesy of Poseidon Scientific
PHASOR DIAGRAM REPRESENTING IMPERFECT CARRIER SUPPRESSION

\[ |\delta|^2 = 1 + (1 + \epsilon)^2 - 2(1)(1 + \epsilon)\cos(\phi) \]

Phase Mismatch = \( \phi \)
Amplitude Mismatch (dB) = \( 10 \log (1 + \epsilon)^2 \)
Carrier Suppression Factor, CS (dB) = \( 10 \log |\delta|^2 \)

Courtesy of Poseidon Scientific
Feedback in Common-Base Amplifier

- $f_t$ of 350 GHz attained in SiGe HBT

- Series-shunt feedback configuration

FOUR STAGE 10 GHz LNA USING JAZZ 0.18 μm SiGe TECHNOLOGY
 (Evaluation Will Be Done to Investigate 1/f Noise of SiGe HBT LNA's;
 Simulated Noise Figure = 2.7 dB with Associated Gain of 26 dB )
10 GHz Low-noise Microwave Amplifier Measurements
Leeson’s Oscillator Noise Model

\[
S^{\text{OSC}}_\phi(f) = \begin{cases} 
  \frac{v_0^2 S_\phi(f)}{4Q^2 f^2} & f < \frac{v_0}{2Q} \\
  S_\phi(f) & f > \frac{v_0}{2Q}
\end{cases}
\]

\[f = v - v_o\]

Fourier frequency (offset frequency)

SLCO Interferometric Stabilized Cavity Loop Oscillator

Feedback oscillator in which the high-Q cavity serves both as the resonator and the discriminator. *Carrier suppression* and *high Q* increase discriminator sensitivity.

Univ. of Western Australia, Poseidon Scientific Instruments, Ivanov, et al., 1998
Impedance-controlled-coupling, Cavity-stabilized DRO/YIG

Cavity stabilization of a DRO or YIG oscillator. Cavity serves as passive discriminator. Carrier suppression and high drive power increase discriminator sensitivity.

J. Dick (JPL), A. SenGupta, F. Walls (NIST) and C. Nelson, B. Riddle (NIST)
Single-fiber Opto Electronic Oscillator (OEO)

Laser → Optical Modulator → Optical Fiber → Photodetector

RF Coupler ← RF Filter ← RF Amplifier

RF Output
Single-fiber Opto Electronic Oscillator (OEO)

Fiber

RF Filter

\[ \frac{c}{n \cdot L} \]

Single Loop OEO

\[ \delta \nu \]

Courtesy of OEWaves, Inc.
Opto-Electronic Oscillator

- OEO has very high Q and frequency agility over a wide range...

- But long fiber OEO has spurs...


Not enough spurious suppression for many RF system needs.
- Worse phase noise performance.
Comparison

• The Multi-loop OEO uses “energy competition” between carrier mode and spur modes to suppress spurs.

• For the Injection-Locked OEO: the spurs from the master OEO cannot be supported by the slave OEO’s.

In principle, spurs can be “eliminated” by destructive interference.

Spurs are suppressed.

Courtesy of Army Res. Lab.
Broadband femtosecond lasers require more careful control of the intracavity dispersion and laser alignment.

In this particular case, the convex mirror provides enhanced self-amplitude modulation which generates shorter pulses and broader spectra.


Courtesy of Scott Diddams, NIST
Dividing Down: Controlling $f_r$ with an Optical Reference

**Femtosecond Comb Optical Divider**

$\text{Femtosecond Laser + Microstructure Fiber}$

PLL 1

$\text{PLL 2}$

$\text{Optical Standard (}f_{\text{Hg}}\text{)}$

Clock Output

$f_r = f_{\text{Hg}} \div m$

(m~10$^6$)

Ultra-low PM Noise from Optical Sources

The Components of an Optical Clock

- Isolated cavity narrows laser linewidth and provides good short-term stability
- Atoms provide long-term stability and accuracy
- Counter accumulates cycles to generate 1 sec

Stable Microwaves from Optical Oscillators

Optical sources now generate some of the most stable microwaves

The femtosecond mode-locked laser comb

Impact of femtosecond lasers on frequency metrology
- Femtosecond laser frequency combs have dramatically
  - Decreased uncertainty
  - Simplified measurements

Femtosecond Lasers Provide...
- Convenient “gear” for optical clocks and a means for comparing clocks
- Linking to virtually all frequency domains (RF – optical)
  - Generation of low noise signals across the optical and microwave domains.
- A new tool for laser spectroscopy
- An opening to new applications and techniques
  - Absolute Femtosecond timing capabilities
  - Secure communications
  - Advanced navigation, sensors, radar, etc.
  - Fundamental physics
  - Ultrafast science

Cavity modes are locked in phase to generate a short pulse once every rounding time 2Nt
10 GHz Low-noise Microwave Oscillator Measurements

-190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 100 1000 10000 100000 1000000 10000000

Frequency (Hz)

L(f) dBc/Hz

- OEWave 16 Km Single Fiber
- Ceramic DRO (York)
- Low Noise QZ with Perfect Multiplier
- SLCO Poseidon (Published data)
- NIST Cavity Stabilized DRO
- Femtosecond Comb
- Calcium Optical (projected)
The End

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Thanks to many contributors.
**Conclusion**

- **Comparison of different classes of microwave amplifiers and oscillators at X-band**

  
  
  
  
  
  
  
Conclusion

- Comparison of different classes of microwave amplifiers and oscillators at X-band

  - “A 3-10 GHz bandwidth low-noise and low-power amplifier for full-band UWB communications in 0.25- /spl mu/m SiGe BiCMOS technology,” Shiramizu, N., Masuda, T., Tanabe, M., Washio, K. Central Res. Lab., Hitachi Ltd., Tokyo, Japan; This paper appears in: IEEE Radio Frequency integrated Circuits (RFIC) Symposium, 12-14 June, 2005.
Low-noise Microwave Oscillator Measurements


L(f) dBc/Hz

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OEWave 16 Km Single Fiber
Low Noise QZ with Perfect Multiplier
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Femtosecond Comb
Calcium Optical (projected)
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Active oscillator in which the high-Q cavity serves both as the resonator and the discriminator. Carrier suppression and high Q increase discriminator sensitivity.
Impedance-controlled-coupling, Cavity-stabilized DRO/YIG

Cavity stabilization of a DRO or YIG oscillator. Cavity serves as passive discriminator. Carrier suppression and high drive power increase discriminator sensitivity.
An Octave-Spanning Comb using Microstructure Fiber

Femtosecond Comb Optical Divider

1 GHz Ring Laser

Pump
532 nm

Ti:Sapphire
Gain

⇒ GigaOptics laser, OFS fiber

With typical microstructured fibers, one needs about 150 pJ of pulse energy in ~30 fs to generate an octave of spectrum. This corresponds to 200 mW average power at a 1 GHz rep rate or 15 mW average power at a 100 MHz rep rate.

Microstructure Optical Fiber

Courtesy of Scott Diddams, NIST
Oscillators’ noise

\[ H \approx H_0 e^{-j\frac{2fQ}{v_0}} \]

\[ A = A_0 e^{j\phi} \]

oscillation condition:

\[ A g H = 1 \]

\[ S_{\phi}^{osc}(f) = \begin{cases} v_0^2 S_{\phi}(f) & f < \frac{v_o}{2Q} \\ 4Q^2 f^2 & f > \frac{v_o}{2Q} \end{cases} \]

Leeson’s model*

\[ f = v - v_o \]

Fourier frequency (offset frequency)

\[ y = \frac{\Delta v}{v_0} \]

Graph with axes:
-\( \sigma_y(\tau) \) on the y-axis (log scale)
-\( \tau \) on the x-axis (log scale)

Key labels:
- \( \tau^{-1} \)
- \( \tau^{-1/2} \)
- \( \tau^0 \)
- \( \tau^{1/2} \)
New calculation

\[ S_x(f) = \sum_{\beta=-4}^{0} h_{\beta} f^{\beta} \quad 0 \leq f \leq f_h \]
Frequency Domain
Power Spectral Density
of phase fluctuations

<table>
<thead>
<tr>
<th>$\beta = \alpha - 2$</th>
<th>Noise type</th>
<th>$\sigma_y(\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>White phase</td>
<td>$\propto \tau^{-1}$</td>
</tr>
<tr>
<td>1</td>
<td>Flicker phase</td>
<td>$\propto \tau^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>Random walk phase</td>
<td>$\propto \tau^{-1/2}$</td>
</tr>
<tr>
<td>3</td>
<td>Flicker frequency</td>
<td>$\propto \tau^1$</td>
</tr>
<tr>
<td>4</td>
<td>Random walk frequency</td>
<td>$\propto \tau^0$</td>
</tr>
</tbody>
</table>

Allan Deviation of fractional frequency fluctuations
Time Domain
References for Advanced Design Techniques

References for Advanced Design Techniques


- “A 3-10 GHz bandwidth low-noise and low-power amplifier for full-band UWB communications in 0.25- /spl mu/m SiGe BiCMOS technology,” Shiramizu, N., Masuda, T., Tanabe, M., Washio, K. Central Res. Lab., Hitachi Ltd., Tokyo, Japan; This paper appears in: IEEE Radio Frequency integrated Circuits (RFIC) Symposium, 12-14 June, 2005.
Examining the circuit it is clear that virtually none of the signal at the output port appears at the input port. C-B amplifier therefore offers excellent reverse isolation.
IV. LEESON’S EQUATION

1. Origins of Phase Noise

A simple feedback loop (phase servo) predicts phase noise from device noise figure, baseband noise sources and resonator Q.

2. Leeson’s Equation

Predicts Spectral Density (PSD) of Phase Fluctuations from 1/f noise, noise figure, carrier power and loaded Q.
\[ S_a(f_m) : \text{Additive white thermal noise power at } f_o. \]

\[ S_a(f_m) = \frac{FkTB}{P_c} = \frac{FkT}{P_c} \quad [\text{Hz}^{-1}] \quad (1) \]

F : noise figure of the amplifier and resonator

k : Boltzmann’s constant

T : Temperature in Kelvin

B : Set to 1 Hz to give \( S_a(f_m) \) as **Power Spectral Density (PSD)**. Then normalize to the oscillator output power, \( P_c \), to give the normalized PSD.
$S_b(f_m)$: Baseband noise sources upconverted by active device non-linearity.

Flicker noise (1/f noise)
Shot noise (white noise)
Thermal (white noise)
Transform the phase servo loop to baseband and combine normalized input noise sources:

Input PSD: \( S_i(f_m) = \frac{FkT}{P_c} + \frac{K_1}{P_c f_m} + \frac{K_2}{P_c} \) [Hz\(^{-1}\)]

\[
\frac{f_r}{2Q_L} = \frac{f_o}{2Q_L
\]

(2)

Noise-free amp (unity gain)
Input Noise Power Spectral Density, $S_i(f_m)$

$$\log[S_i(f_m)] (\text{Hz}^{-1})$$

The intersection of the $K_1/f_m$ and $FkT/P_c$ is the corner frequency, $f_c$.

$$S_i(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m}\right) \text{[Hz}^{-1}]$$ (3)
2. Leeson’s Equation

Leeson’s equation for the Power Spectral Density of an oscillator:

\[
S_o(f_m) = \left[ 1 + \left( \frac{f_o}{2Q_L f_m} \right)^2 \right] S_i(f_m)
\]

\[
S_i(f_m) = \frac{F k T}{P_c} \left( 1 + \frac{f_c}{f_m} \right) \text{ [Hz}^{-1}] \]

\[
S_o(f_m) = \frac{F k T}{P_c} \left( 1 + \frac{f_c}{f_m} \right) \left[ 1 + \left( \frac{f_o}{2Q_L f_m} \right)^2 \right] \text{ [rad}^2/\text{Hz}] \]

Equal to Spectral Density of Phase Fluctuations, [rad}^2/\text{Hz}], when AM noise is negligible.
2. Leeson’s Equation, cont.

\[ S_\phi(f_m) = S_o(f_m) = \frac{FkT}{P_c} \left( 1 + \frac{f_c}{f_m} \right) \left[ 1 + \left( \frac{f_o}{2Q_Lf_m} \right)^2 \right] \text{ [rad}^2/\text{Hz}] \]

Single Sided Spectral Density of Phase Fluctuations, [rad\(^2\)/Hz], versus offset frequency, \( f_m \).
Using Leeson’s Equation to Predict Oscillator Phase Noise

\[ S_\phi (f_m) = S_o (f_m) = \frac{FkT}{P_c} \left( 1 + \frac{f_c}{f_m} \right) \left[ 1 + \left( \frac{f_o}{2Q_L f_m} \right)^2 \right] \text{ [rad}^2/\text{Hz]} \]

\[ S_\phi (f_m) = 2L(f_m) \]

Oscillator resonator bandwidth: \( f_r = \frac{f_o}{2Q_L} \)

\[ L(f_m) = \frac{FkT}{2P_c} \left( 1 + \frac{f_c}{f_m} \right) \left[ 1 + \left( \frac{f_r}{f_m} \right)^2 \right] \text{ [dBc/Hz]} \]

Consider two cases:

1. High-Q oscillator: \( f_c > f_r \),
2. Low-Q oscillator: \( f_c < f_r \).
\[ L(f_m) = \frac{FkT}{2P_c} \left( 1 + \frac{f_c}{f_m} \right) \left[ 1 + \left( \frac{f_r}{f_m} \right)^2 \right] \]

\[ S_\phi(f_m) = 2L(f_m) \quad [\text{rad}^2/\text{Hz}] \]
# Comparison of Candidate Oscillators

<table>
<thead>
<tr>
<th>Oscillator</th>
<th>High Power Air Cavity</th>
<th>SLCO Poseidon</th>
<th>OEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output coupling</td>
<td>Very Low</td>
<td>Moderate</td>
<td>Directional coupler and amplifier</td>
</tr>
<tr>
<td>Resonator Q</td>
<td>Moderate 60,000</td>
<td>High 190,000</td>
<td>Very High 1e9</td>
</tr>
<tr>
<td>Loop Power</td>
<td>High 1-10 Watts</td>
<td>Moderate 100's mW</td>
<td></td>
</tr>
<tr>
<td>Inherent Spurs</td>
<td>None</td>
<td>None</td>
<td>Many</td>
</tr>
</tbody>
</table>
Interferometric Cavity Stabilized DRO/YIG
Amplifier Comparison

aPROPOS PM noise, goal, and four existing amplifiers (@ 10 GHz)

-200 -190 -180 -170 -160 -150
-140 -130 -120 -110 -100 -90 -80 -70 -60
-50 -40 -30 -20 -10 0

1 10 100 1000 10000 100000 1000000 10000000

L(f) dBc/Hz

Projected amp. spec, Pin=0 dBm
MSH-6135501, Pin=+2.57 dBm
MSH-6133401, Pin=+2.57 dBm
HMCC-5618 #1, Pin=+3.7 dBm
HMCC-5618 #2, Pin=+3.7 dBm
Mayo FFA, Pin=0 dBm
NIST Array, Pin=0 dBm
Typical Microwave Amplifier
Noise Floor of Measurement System

Frequency (Hz)
MAYO First Feedfoward Amp Results

12/17/04 aPROPOS amplifier PM noise, goal (@ 10 GHz)

Projected amp. spec, Pin=0 dBm
Mayo FFA, Pin=0 dBm
NIST Array, Pin=0 dBm
OE Waves Loop Amp, Pin=-20 & +10 dBm
Noise Floor of Measurement System

Frequency (Hz)
L(f) dBc/Hz