Low Noise Oscillator Design and Performance

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- Basic Oscillator Operation
- Types of Resonators and Delay Lines
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- Environmental Stress Effects
- Oscillator Circuit Simulation & Noise Modeling
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1. Short-term Frequency/Phase/Amplitude Stability
Types of Phase and Amplitude Noise

Signal Spectral Amplitude (dB)

- Multiplicative (i.e., 1/f AM & 1/f PM)
- Additive
- Carrier Signals

Baseband flicker (1/f) noise

Signal Frequency (Hz)

fo

fo'
Types of Phase and Amplitude Noise (cont.)

Additive Noise [noise power independent of signal]

<table>
<thead>
<tr>
<th>Type</th>
<th>Formula</th>
<th>Constants/Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal noise</td>
<td>$e_n^2 = 4KTRB$</td>
<td>$K = \text{Boltzman’s constant} = 1.374 \times 10^{-22}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T = \text{temp in Kelvin} = 300K \text{ at room temp.}$</td>
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<td></td>
<td></td>
<td>$R = \text{resistance in ohms}$</td>
</tr>
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<td></td>
<td></td>
<td>$B = \text{bandwidth}$</td>
</tr>
<tr>
<td>Shot noise</td>
<td>$i_n^2 = 2qIB$</td>
<td>$q = 1.59 \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I = \text{current in amperes}$</td>
</tr>
</tbody>
</table>
### How to Calculate Additive Noise

**Amplifier additive noise power**

KTBF ($R_g=50$ ohms, $T=300K$, $B=1$Hz), referred to input = $-174\text{dBm/Hz} + NF(\text{dB})$

**Carrier Signal-to-Noise Ratio**

in dBC/Hz = $-174 + NF(\text{dB})$ - input signal power (dBm)

**One-half noise power is AM, One-half PM**

in dBC/Hz = $-177 + NF(\text{dB})$ - input signal power (dBm)
Characteristics of Multiplicative Noise

- An example of multiplicative noise is a noise component in the transmission gain magnitude (AM noise) and phase (PM noise) in an amplifier.
- The noise component can equivalently occur in a transistor, for example, as noise-like variation in the transconductance ($g_m$) or junction capacitance.
- Device multiplicative AM and PM noise levels usually are non-identical.
- Multiplicative noise level can be affected by non-linearity (i.e., in-compression amplifier operation).
- Multiplicative noise most often occurs as flicker-of-amplitude and flicker-of-phase modulation, or $1/f$ AM and $1/f$ PM.
The spectral level of the 1/f AM and PM noise decreases at a rate of 10dB/decade with increasing carrier offset (modulation) frequency.

In (oscillator sustaining stage) transistor amplifiers:
- Relatively low 1/f AM and PM noise is observed in silicon bipolar and HBT transistor amplifiers operating at and below L-band.
- Highest 1/f AM and PM noise is observed in microwave GaAs FET amplifiers.

1/f AM and PM noise is also observed in passive devices. 1/f variation in quartz crystal and SAW resonator impedance(s) is often the main source of near-carrier noise in oscillators using these resonators.
Characteristics of Multiplicative Noise (continued)

- Other mechanisms resulting in carrier signal noise-modulation include:
  - Noise on device DC power supplies
  - Noise-like environmental stress (especially vibration)

- $1/f$ AM and $1/f$ PM noise levels vary (widely) from vendor-to-vendor for similar performance devices and can vary significantly for the same component on a device-to-device basis.

- It is necessary to evaluate noise performance via measurement of purchased/sample devices.

- In an oscillator, amplifier $1/f$ PM noise is converted to higher level $1/f$ FM at carrier offset frequencies within the resonator half-bandwidth.
“Typical” Component 1/f PM Multiplicative Noise Levels

Phase Noise Sideband Level (dBc/Hz)

Carrier Offset Frequency (Hz)

X-band GaAs Amp.
X-band Schottky Mixer & X-band HBT amp.
L-band Bipolar and HBT Amp.
HF-VHF Bipolar Amp. & HF-UHF Schottky Mixer
Component 1/f Instability

- The non-semiconductor components in the oscillator circuit also exhibit short-term instability.
- “Passive” components (resistors, capacitors, inductors, reverse-biased, varactor diodes) exhibit varying levels of flicker-of-impedance instability whose effects can be comparable to or higher than to that of the sustaining stage amplifier 1/f AM and PM noise in the oscillator circuit.
- The oscillator frequency control element (i.e., resonator) can exhibit dominant levels of flicker-of-resonant frequency instability, especially acoustic resonators.
- In an open loop sense, the resonator instability can be plotted as flicker-of-phase noise (induced on a carrier signal passing through the resonator).
Passive Component 1/f Impedance Instability

-110
-120
-130
-140
-150
-160
-170

PSD (DX/X)^2 in dB

Carrier Offset Frequency (Hz)

1 10 100 1K 10K 100K 1M

X-band GaAs Amp.
X-band Schottky Mixer & X-band HBT amp.
L-band Bipolar and HBT Amp.
HF-VHF Bipolar Amp. & HF-UHF Schottky Mixer

HF Varactor diodes, Ceram. Capacitors, Powdered Iron Inductors
VHF Varactor & PIN diodes, Ceram. Capacitors, Powdered Iron Inductors
Resonator Open Loop Phase Instability

- **Carrier Offset Frequency (Hz)**
- **Phase Noise Sideband Level (dBc/Hz)**
  - X-band GaAs Amp.
  - X-band Schottky Mixer & X-band HBT amp.
  - L-band Bipolar and HBT Amp.
  - HF-VHF Bipolar Amp. & HF-UHF Schottky Mixer
  - Low Noise HF/VHF BAW
  - Low Noise UHF SAWR/STWR
PM-to-FM Noise Conversion in an Oscillator

\[ \tau = \text{oscillator closed loop group delay} \]
\[ \frac{1}{2\pi\tau} = \text{BW/2 for a single (1 pole) resonator} \]

Additional signal noise degradation due to resonator FM noise

Oscillator closed loop signal FM noise due to sustaining stage open loop PM noise

Oscillator sustaining stage open loop PM noise

\[ \text{Phase Noise Sideband Level (dBc/Hz)} \]

\[ \text{Carrier Offset Frequency (Hz)} \]
Commonly Used Measures of Oscillator Signal Short-Term Frequency Stability

-Time Domain: \( \sigma_y(\tau) = \) Two sample deviation (square root Allan Variance)
\[
\sigma_y(\tau) = \frac{1}{2} \left( y_{k+1} - y_k \right)^2
\]

-Frequency Domain:
\( \mathcal{L}(f) = \) Single sideband phase noise-to-carrier power ratio in a 1Hz bandwidth at a offset frequency \( f \) from the carrier (dBc/Hz)
\( S_\phi(f) = \) Spectral density of the phase fluctuations (rad\(^2\)/Hz).
\( S_y(f) = \) Spectral Density of the fractional frequency fluctuations (1/Hz).
\[
S_y(f) = \left( \frac{f}{\nu_o} \right)^2 S_\phi(f), \quad \mathcal{L}(f) = 10 \log(S_\phi(f)/2)
\]
\( \nu_o = \) carrier frequency
Types of Frequency/Phase Noise Spectra

Frequency Domain

$\xi(f)$ (dBc/Hz)

- Random walk: 40 dB/decade
- Flicker of frequency: 30 dB/decade
- White frequency: 20 dB/decade
- Flicker of phase: 10 dB/decade
- White phase: 0 dB/decade

Time Domain

- $\tau^{1/2}$
- $\tau^0$
- $\tau^{-1/2}$
- $\tau^{-1}$
- $\sigma_y(\tau)$

1 Hz

1 sec

Frequency

Time
If the nature of the noise spectra is known to dominate over a large carrier offset region, the Allan Variance can be calculated from the frequency domain data using the appropriate conversion equations. The equations differ, depending on the type of noise (random walk, etc.)
### Short-Term Frequency/Phase/Time Stability Relationships

\[
L(f) \text{ indBc/Hz} = 10\log\left(\frac{S_\phi(f)}{2}\right) = 10\log\left(\frac{v_0}{f}\right)^2 S_y(f)/2
\]

\[
v_0 = \text{carrier frequency}
\]

\[
f = \text{fourier frequency}
\]

Relationships between \(S_y(f)\) and \(\sigma_y(t)\):

<table>
<thead>
<tr>
<th>(S_y(f) = H_\alpha f_\alpha)</th>
<th>(S_y(f) = a \sigma_y(t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha = 2) (white phase)</td>
<td>((\frac{2\pi}{\tau^2 f^2})/(3f_h))</td>
</tr>
<tr>
<td>(\alpha = 1) (flicker noise)</td>
<td>((\frac{2\pi}{\tau^2 f^2})/(1.038 + 3 \ln(\omega \tau)))</td>
</tr>
<tr>
<td>(\alpha = 0) (white frequency)</td>
<td>(2\tau)</td>
</tr>
<tr>
<td>(\alpha = -1) (flicker frequency)</td>
<td>(1/(2f \ln(2)))</td>
</tr>
<tr>
<td>(\alpha = -2) (random walk frequency)</td>
<td>(6/(2\pi)^2 \tau f^2)</td>
</tr>
</tbody>
</table>
### Example: Conversion from Frequency to Time Domain

Suppose a 100MHz Crystal Oscillator signal spectrum in the region around $f=100\text{Hz}$ is flicker-of-frequency with:

$$\mathcal{L}(f=100\text{Hz}) = -120\text{dBc/Hz}$$

Then $S_y(f)$ in the same region:

$$S_y(f) = (10^{\mathcal{L}(f)/10})2f/v_o = (10^{-12})(200/10^8)=2 \times 10^{-22}/f$$

And (from the conversion formula for flicker-of-frequency noise):

$$\sigma_y^2(\tau) \text{ in the region}$$

$$\tau = 1/f = 1\text{sec} = (2)(\ln(2))(S_y(f))(f) = 2.77 \times 10^{-22}$$

therefore, $\sigma_y(\tau) = 1.66 \times 10^{-11}$
2. Basic Oscillator Operation
Oscillator Viewed as a Two Terminal Negative Resistance Generator

\[ Z_{\text{in at } f_0} = jX_r + R_r \]

\[ Z_{\text{in at } f_0} = jX_{\text{in}} + R_{\text{in}} \quad (R_{\text{in}} \text{ is negative}) \]

Conditions for start-up: \( X_r = -X_{\text{in}}, \ R_r + R_{\text{in}} < 0 \)

Steady State: \( X_r = -X_{\text{in}}, \ R_r + R_{\text{in}} = 0 \)
Oscillator Viewed as a Feedforward Amplifier with Positive Feedback

Conditions for start-up: \( G_{M1} G_A G_{M2} G_{M3} G_R > 1, \phi_{M1} + \phi_A + \phi_{M2} + \phi_{M3} + \phi_R = 2N\pi \) radians

Steady State: \( G_{M1} G_A G_{M2} G_{M3} G_R = 1, \phi_{M1} + \phi_A + \phi_{M2} + \phi_{M3} + \phi_R = 2N\pi \) radians
Symmetrical diode waveform clipping provides better (harder) limiting, compared to single-ended clipping, and appears to provide more immunity from the effects of diode noise. The least noisy form of transistor amplifier gain compression is single-ended current limiting, rather than voltage limiting (saturation). Single-ended limiting is soft limiting.

(1) Instantaneous signal amplitude limiting/waveform clipping via sustaining stage amplifier gain compression or separate diode waveform clipping.

(2) Gain reduction using a feedback control loop. The oscillator RF signal is DC-detected, and the amplified detector output fed to a variable gain control element (i.e., PIN attenuator) in the oscillator.

*Symmetrical diode waveform clipping provides better (harder) limiting, compared to single-ended clipping, and appears to provide more immunity from the effects of diode noise. The least noisy form of transistor amplifier gain compression is single-ended current limiting, rather than voltage limiting (saturation). Single-ended limiting is soft limiting.
Oscillator Turn-On Behavior

- Oscillation is initiated by spectral components of circuit noise and/or DC turn-on transients occurring at the frequency where the small signal conditions for oscillation are satisfied.

- Turn-on time is determined by the:
  - initial noise/transient spectral signal level,
  - steady-state signal level,
  - oscillator loop (resonator loaded Q) delay,
  - and small signal excess gain.
Conversion of Phase to Frequency Instability in an Oscillator

If a phase perturbation, \( \delta \phi \) occurs in an oscillator component (i.e., sustaining stage amplifier phase noise), the oscillator signal frequency must change in order to maintain constant (2\( \pi \) radians) loop phase shift.

The amount of signal frequency change caused by the phase perturbation is related to the oscillator loop group delay (i.e., resonator loaded Q).

This conversion results in significant signal spectral degradation at carrier offset frequencies within \( f = 1/2\pi \tau \) where \( \tau \) is the loop group delay (1/2\( \pi \tau = BW/2 \) for a single resonator).

\[ \tau = \delta \phi / 2\pi \delta f \]

\[ \delta f = \delta \phi / 2\pi \tau \]
The conversion process can be described by:

- Closed-loop \( S_{\phi}(f) = \text{open-loop } S_{\phi}(f)(1/2\pi f)^2 \)
- Noise sideband level = \( \mathcal{L}(f) = 10\text{LOG}(S_{\phi}(f)/2) \)
PM-to-FM Noise Conversion in an Oscillator

- Additional signal noise degradation due to resonator FM noise
- Oscillator closed loop signal FM noise due to sustaining stage open loop PM noise
- Oscillator sustaining stage open loop PM noise

Phase Noise Sideband Level (dBc/Hz)

1/f FM

1/f PM

white FM

white PM

\[ \tau = \text{oscillator closed loop group delay} \]
\[ \frac{1}{2\pi\tau} = \text{BW/2 for a single (1 pole) resonator} \]
Characteristics of Ideal Resonator

- High group delay (high resonator loaded Q)
- High operating frequency
- Low Loss
- Moderate Drive Capability
- Low frequency sensitivity to environmental stress (vibration, temperature, etc.)
- Good short-term and long-term frequency stability
- Accurate frequency set-on capability
- External frequency tuning capability
- No undesired resonant modes or higher loss in undesired resonant modes or undesired resonant mode frequencies far from desired operating frequency
- High manufacturing yield of acceptable devices
Characteristics of Ideal Oscillator Sustaining Stage

- Low multiplicative (1/f AM and especially 1/f PM) noise
- Low additive noise (good noise figure)
- Drive capability consistent with resonator drive level and loss
- Low noise in ALC/AGC circuits and/or in-compression amplifier operation
- Low gain and phase sensitivity to DC supply and circuit temperature variations
- Low group delay (wide bandwidth)
- High load circuit isolation
- High MTBF; minimal number of adjustable components
- Ease of alignment and test
- Good DC efficiency
- Low cost
3. *Types of Resonators and Delay Lines*
Types of Resonators and Delay Lines

1. Lumped Element (L-C)
2. Acoustic
   - Bulk Acoustic Wave (BAW)
   - Surface Acoustic Wave (SAW)
   - Surface Transverse Wave (STW)
3. Distributed Element
   - (transmission line)
   - Helical
   - Microstrip and Stripline
   - Dielectric Loaded Coaxial
4. Dielectric
5. Cavity, Waveguide
6. Optical Fiber
7. Whispering Gallery Mode, Sapphire Dielectric

Highlighted types used in lower noise oscillators
Quartz Acoustic Resonators

Desirable Properties
- Very high Q
- Controllable (selectable) frequency temperature coefficient
- Excellent long-term and short-term frequency stability
- Relatively low cost
- Moderately small volume (especially SAW, STW)
- Well defined, mature technology

Undesirable Properties
- 1/f FM noise that often exceed effects of sustaining stage 1/f PM noise
- Unit-to-unit 1/f FM noise level variation; high cost associated with low yield of very low noise resonators
- BAW resonator drive level limitations: 1-2mW for AT-cut, 5-7mW for SC-cut, even lower drive for low drift/aging
- Non-uniform vibration sensitivity
- FOM (loaded Q) decreases with increasing frequency
Quartz Crystals Electrical Equivalent Circuit
(for widely used AT-cut and SC-cut crystals)

\[ f_{ss} = \frac{1}{2\pi(L_m C_m)^{0.5}} \]

- L_m = motional (series) inductance
- C_m = motional capacitance
- R_s = series resistance
  \[ 2\pi f_s / R_s = \text{unloaded } Q \]

- Third overtone resonance, \( f = 3f_s \)
- Fifth overtone resonance, \( f = 5f_s \)
- Anharmonic and higher odd-overtone resonance(s)

Quartz Acoustic Resonators, continued
## Improvements in Acoustic Resonator Performance - 1985 to 1999

<table>
<thead>
<tr>
<th>Year</th>
<th>Resonator Type</th>
<th>Frequency</th>
<th>Noise Level, $S_y(f=100\text{Hz})$</th>
<th>$P_{\text{max}}$ (mW)</th>
<th>Virbration Sensitivity (parts in $10^{-10}/g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nominal Best</td>
<td></td>
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</tr>
<tr>
<td>1985</td>
<td>5th OT AT-cut</td>
<td>80MHz</td>
<td>$1 \times 10^{-24}$ $2 \times 10^{-25}$</td>
<td>2</td>
<td>5 to 20</td>
</tr>
<tr>
<td>1985</td>
<td>Raytheon SAW</td>
<td>500MHz</td>
<td>$2 \times 10^{-24}$ $4 \times 10^{-25}$</td>
<td>50</td>
<td>5 to 50</td>
</tr>
<tr>
<td>1989</td>
<td>5th OT AT-cut</td>
<td>40MHz</td>
<td>$5 \times 10^{-26}$ $1 \times 10^{-26}$</td>
<td>2</td>
<td>10 to 30</td>
</tr>
<tr>
<td>1989</td>
<td>3rd OT S C-cut</td>
<td>80MHz 100MHz</td>
<td>$2 \times 10^{-25}$ $4 \times 10^{-26}$</td>
<td>7</td>
<td>3 to 10</td>
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<tr>
<td>1995</td>
<td>5th OT S C-cut</td>
<td>160MHz</td>
<td>$1 \times 10^{-25}$ $2 \times 10^{-26}$</td>
<td>7</td>
<td>3 to 10</td>
</tr>
<tr>
<td>1995</td>
<td>SAWTEK STW</td>
<td>1000MHz</td>
<td>$5 \times 10^{-24}$ $1 \times 10^{-24}$</td>
<td>100</td>
<td>1 to 3</td>
</tr>
<tr>
<td>1999</td>
<td>FEI OT S C-cut</td>
<td>100MHz</td>
<td>???</td>
<td>$\leq 1.6 \times 10^{-26}$</td>
<td>???</td>
</tr>
</tbody>
</table>
**Dielectric-Filled Coaxial Resonators**

- Very popular in wireless hardware
- High drive capability
- One piece, plated construction results in low vibration sensitivity
- Unloaded Q is only moderate (proportional to volume)
- $L(100\text{Hz}) = -100\text{dBc/Hz}$, with $-178\text{dBc/Hz}$ noise floor achieved at 640MHz using large volume resonators as multi-pole filter oscillator stabilization elements
- Even though resonators are “passive”, excess 1/f noise has been measured in large volume, high delay devices with variations in 1/f noise level of up to 20dB
Dielectric Resonators

Advantages
- High Q at high (microwave) frequency
- No measurable resonator 1/f noise
- High drive capability
- Near-zero temperature coefficient for some ceramic dielectric materials
- Amenable to mechanical adjustment and electronic frequency tuning

Disadvantages
- Substantial Q degradation unless cavity volume is large compared to that of dielectric (low order mode resonances)
- Highest Q with modest volume occurs above C-band where sustaining stage amplifiers are primarily GaAs sustaining stage amplifiers exhibiting relatively high 1/f AM and PM noise
- Resonator frequency sensitivity to vibration is typically 10 to 100 times higher, compared to BAW, SAW resonators
Multiple Resonators Can Provide Lower Noise

- Multiple resonators can be cascaded (isolated by amplifiers) or used in multi-pole filters in order to increase the oscillator open loop signal path group delay.

- Analysis shows that for a given net insertion loss, increasing the filter order beyond 2-pole does not result in significant increase in group delay.

- The group delay increase (going from 1 pole to 2 poles) for net loss in the range 3dB to 15dB is 17% to 60%.
  - Increasing the number of poles does result in an increase in the bandwidth over which the group delay is maximum.
  - Use of a single, multi-pole filter at a given, net insertion loss results in approximately the same delay as a cascade of resonators having the same overall insertion loss.
## Optical Fiber Delay Lines

### Advantages
- High delay possible: tens of microseconds
- Low optical signal strength loss in fiber
- Opto-electronic Oscillator (OEO) signal generation directly at microwave
- Noise level (i.e., delay) theoretically independent of carrier frequency
- Possible generation of multiple, selectable frequency signals (spaced at the reciprocal of the delay time)

### Disadvantages
- Detector and/or microwave amplifier noise may limit attainable performance
- For low noise signal generation, long fiber length results in conditions for oscillation being satisfied at multiple, closely-spaced frequencies
- Selectable (reciprocal of delay) frequencies are non-coherent
Opto-Electronic Oscillator (OEO)

Other refinements include use of a second, shorter length optical fiber for selection (in-phase reinforcement) of a specific frequency signal and use of carrier suppression for additional noise reduction.

Approximately -84dBc/Hz at fm=100Hz demonstrated at 10GHz using carrier suppression. This level of near-carrier PM noise is comparable to that obtainable using frequency-multiplied, quartz crystal oscillator or SAW oscillator-derived, X-band signal.

Spectral Tradeoff: Near-Carrier vs Noise Floor Performance

Carrier Offset Frequency (Hz)

Spectral Tradeoff: Near-Carrier vs Noise Floor Performance

- S-Band Dielectric Resonator Oscillator
  - Signal Multiplied to X-Band
    - 15dB typ.
    - 10dB typ.

- 1GHz Quartz SAW or STW Oscillator
  - Signal Multiplied to X-Band
    - 10dB typ.

- 100MHz Quartz Crystal Oscillator
  - Signal Multiplied to X-Band
    - 10dB typ.

\( \dot{\phi}(f) \) (dBc/Hz)
Dielectric loss in sapphire is low at room temperature and rapidly decreases with decreasing temperature.

High-order “whispering gallery” mode ring and solid cylindrical resonators have been built that exhibit unloaded Q values, at X-band, of 200,000 at room temperature and 5 to 10 million at 80K.

This ultra-high resonator Q results in oscillators whose X-band output signal spectra are significantly superior to that attainable using any other resonator technology.
Whispering Gallery Mode, Sapphire Dielectric Resonators: Issues

- Resonator volume (including hermetic, cooled enclosure) is relatively large.
- The ultra-low phase noise spectrum exhibited by the oscillator is degraded by correspondingly low levels of vibration.
- For cryo-cooled resonators, cryo-cooler vibration, MTBF, cost, etc. constitute overall hardware performance issues. Vibration-free, TE-coolers are inefficient with limited cooling capability. Resonant frequency temperature coefficient is large at elevated (i.e., TE-cooler) temperatures.
- Addition of temperature compensating materials usually degrades resonator Q.
- GaAs sustaining stage amplifiers exhibit high 1/f PM noise that degrades oscillator near-carrier signal spectral performance. Noise reduction feedback circuitry adds cost/volume/complexity to the oscillator circuit.
Measured Performance: TE-Cooled, Sapphire DRO

Poseidon Scientific Instruments (PSI) Sapphire DRO
Phase Noise at 9GHz

Phase Noise Sideband Level (dBC/Hz)

Frequency (Hz)
4. Useful Network/Impedance Transformations
Impedance Matching and Transformations

- Useful for matching non-50 ohm devices to 50 ohms or to each other.

- A standard tool used extensively in the design of band-pass or band-reject filters allowing use of practical component element values.

- Very useful in oscillator design, both within the sustaining circuit stage itself and also for matching between oscillator functional elements (i.e., resonator and resonator tuning circuitry).
Series - Parallel Reactance/Resistance Conversions

Example: If $R_p = 300$ ohms and $X_p = j100$ ohms at frequency $f_0$, then “$Q$” = 3 at (and only at $f_0$), this is equivalent to $R_s + jX_s = 30 + j90$

The “$Q$” is an approximate measure of the bandwidth of the transformation (i.e., $BW = f_0/Q$)
**Delta-Star Transformation**

- Often results in being able to obtain more realistic element values (component impedance levels)

\[
\begin{align*}
\sum ZZ &= \frac{ZaZb + ZaZc + ZbZc}{Zb} \\
Zx &= \frac{\sum ZZ}{Zb} \\
Zy &= \frac{\sum ZZ}{Zc} \\
Zz &= \frac{\sum ZZ}{Za}
\end{align*}
\]
Norton’s Transformation

- Very powerful and useful
- Not a single frequency approximation, a true transformation
- Negative value, reactive element can usually be absorbed into existing, adjacent positive value similar reactive element
Chebyshev Impedance Transforming Networks [1]

- Tabulated impedance ratios from 1.5:1 to 50:1 and bandwidths from 10% to 100%
- Can be lumped or distributed element

Quarter-wavelength Impedance Inverters, Impedance Transformers, and Delay Lines (phase shift)

\[ Z_{in} = Z_0^2/R_L \]

characteristic impedance \( = Z_0 \)

\[ Z_{in} = (Z_{01}^2/Z_{02}^2)R_L \]

characteristic impedance \( = Z_{01} \)

characteristic impedance \( = Z_{02} \)

Lumped element approximations for a quarter-wavelength lines
Transmission Lines: Lumped Element Approximations

If the line is considered a series of pi networks, the inner capacitor values are twice that of the end capacitors (i.e., $C_2 = 2C_1$)

$L_{\text{total}} = (\ell / \lambda)(Z_0 / f_0)$, $C_{\text{total}} = (\ell / \lambda)(1 / (Z_0 f_0))$, $L_{\text{total}}/C_{\text{total}} = Z_0^2$

Single-ended lines (coaxial, microstrip, stripline)

Balanced lines (twin-lead, twisted pair)
Useful Aspects of Lumped or Distributed Element Transmission Lines

- Impedance inversion/transformation (can transform a resonator series-resonance impedance to a parallel resonance)
- Relatively broadband impedance transformation, compared to band-pass structures (lower sensitivity to element value tolerance, temperature coefficient, etc.)
- All or some of the line can be realized using actual transmission line (coaxial cable)
  - Thermal isolation of ovenized components
  - Vibration isolation of acceleration sensitive components
- At HF and Low VHF, transmission line transformers can be realized with values for characteristic impedance not obtainable using conventional coaxial or twin lead cable
- Positive or negative phase shifts may be obtained using high-pass or low-pass lumped element approximations
Dipole Transformation

Quartz Crystal with Parallel Capacitance Anti-resonated

Varactor Inductor Tuning Circuit

The series resonant frequency of a high Q dipole is unaffected by movement of parallel elements from one portion of the dipole to the other as long as series and parallel resonant frequencies do not approach one another.
5. Sustaining Stage Design and Performance
Zin (ideal voltage-controlled current source) = Z1 + Z2 + gm(Z1)(Z2)

If Z1 and Z2 are reactances, Z1=jX1, Z2=jX2, and
Zin = j(X1+X2) -gm(X1)(X2)

where -gm(X1)(X2) is the negative resistance term

The Transistor Viewed as a Reactance-plus-Negative Resistance Generator

u Normally, capacitors are used for the reactances X1 and X2

u At microwave frequencies, transistor junction capacitance may comprise a significant part or all of the reactance
The Transistor Viewed as a Negative Resistance Generator (at $\omega_0$)

$Z_{in}$ (ideal voltage-controlled current source)

$= \frac{(Z1)(Z2)}{(Z1+Z2+Z3)} + \frac{1}{gm}$

If $Z1=1/j\omega C1$, $Z2=1/j\omega C2$, and $Z3=j\omega Ls+Rs$

and if, at $\omega = \omega_0$, $Z1/Z2/Z3$ are resonant

($Z1+Z2+Z3 = Rs$),

then $Z_{in}$ at $\omega = \omega_0 = -1/(\omega_0^2 C1 C2 Rs) + 1/gm$

u Normally, capacitors are used as the impedances $Z1$ and $Z2$

u $Z3$ is normally an inductor, and the net resonant resistance of the series combination, $Rs$, includes that due to the circuit external load resistance as well as the loss in the inductor
Zin = j(X1+X2) - (X1)(X2)/(RE+1/gm)

where -(X1)(X2)/(RE+1/gm) is the negative resistance term

The addition of RE stabilizes the negative resistance (makes it more dependent on RE then on gm)

In addition, un-bypassed emitter resistance constitutes one method for reducing transistor 1/f PM noise levels
Crystal Oscillators with Crystal Placement in Different Portions of the Circuit

- Crystal operation above $f_s$ where $Z_{Y_1} = j\omega L_s + R_s$
- Crystal operation at $f_s$ where $Z_{Y_1} = R_s$ (i.e., $Z = R_E$)

Diagram showing basic oscillator circuit.
**Methods for Reducing Discrete Transistor Sustaining Stage 1/f PM Noise**

- Use un-bypassed emitter resistance (a resistor or the resonator itself connected in series with the emitter).
- Use high frequency transistors having small junction capacitance and operate at moderately high bias voltage to reduce phase modulation due to junction capacitance noise modulation.
- Use heavily bypassed DC bias circuitry and regulated DC supplies.
- Consider the use of a base-band noise reduction feedback loop.
- Extract the signal through the resonator to the load, thereby using the resonator transmission response selectivity to filter the carrier noise spectrum.

* From the NIST Tutorial on 1/f AM and PM Noise in Amplifiers
Extraction of the Oscillator Signal Through the Resonator

Transformer sometimes used to step up current into Q1, Q2

Matching Network
Discrete Transistor Oscillator Example: Low Noise, VHF Crystal Oscillator

Ferrite beads to prevent UHF oscillation

Ref. bias (RF level adjust)

Symmetric diode clipping

Cascode transistor configuration (large ratio of $P_0/P_{Y1}$)
## Discrete Transistor Sustaining Stages

### Advantages

- **Low Cost**
- **Pre-fabrication and post-fabrication design and design change flexibility**
- **Biasing flexibility**
- **Efficiency (DC power consumption)**

### Disadvantages

- **For low noise, transistors with high $f_t$ should be used; circuit is then susceptible to high frequency instability due to layout parasitics and loss-less resonator out-of-band impedance**
- **Difficulty in predicting or measuring 1/f AM and PM noise using 50 ohm test equipment since actual sustaining stage-to-resonator circuit interface impedances are not usually 50 ohms.**
Advantages of Modular Amplifier
Sustaining Stages

- Easily characterized using 50 ohm test equipment (amplifier s-parameters, 1/f AM, 1/f PM, and KTBF noise)
- Availability of unconditionally stable amplifiers eliminates possibility of parasitic oscillations
- Amplifiers available (especially silicon bipolar and GaAs HBT types) exhibiting low 1/f AM and PM noise
- Certain models maintain low noise performance when operated in gain compression thereby eliminating a requirement for separate ALC/AGC circuitry in the oscillator
- Amplifier use allows a building block approach to be used for all of the oscillator functional sub-circuits: amplifier, resonator, resonator tuning, resonator mode selection filter, etc
- Relatively low cost amplifiers (plastic, COTS, HBT darlington pair configuration) are now available with multi-decade bandwidths operating from HF to microwave frequencies
Silicon Bipolar Modular Amplifier: Measured 1/f PM Noise
“Typical” Component 1/f PM Multiplicative Noise Levels

Phase Noise Sideband Level (dBc/Hz)

Carrier Offset Frequency (Hz)

-170  -160  -150  -140  -130  -120  -110

-10  -100  1K  10K  100K  1M

X-band GaAs Amp.

X-band Schottky Mixer & X-band HBT amp.

L-band Bipolar and HBT Amp.

HF-VHF Bipolar Amp. & HF-UHF Schottky Mixer
Modular Amplifiers: General Comments

- Generally, amplifier vendors do not design for, specify, or measure device 1/f AM and PM noise.

- It is usually necessary to evaluate candidate sustaining stage amplifiers in terms of measured 1/f AM and PM noise at intended drive level (i.e., in gain compression when the oscillator will not employ separate ALC/AGC).

- Amplifier $S_{21}$ phase angle sensitivity to gain compression, as well as gain magnitude and phase sensitivity to DC supply variation (noise) must be considered.

- Silicon bipolar amplifiers and HBT amplifiers operating below L-band normally exhibit lower levels of 1/f AM and PM noise, compared to microwave amplifiers.
Modular Amplifier Oscillator Design
Example: Low Noise, SAWR Oscillator

- \( X_s = \) Select-in-test inductor or capacitor to align SAWR center frequency
- Four, cascaded combinations of SAWRs and amplifiers used to increase loop group delay
- Achieved -124dBc/Hz at \( f_m=100\text{Hz} \) at \( f_0=320\text{MHz} \)
- Requires accurate tracking between resonators over time and temperature
Quarter-wavelength lines yield 90° phase shift and match 50 ohms to Zx at fo, provide improper phase shift below fo and attenuation above fo preventing oscillation at other crystal resonant modes (previous exercise)

Demonstrated -156dBc/Hz at fm=100Hz at fo=10MHz using third overtone AT-cut crystals
6. Oscillator Frequency Adjustment/Voltage Tuning
**Methods for Providing Oscillator Frequency Tuning**

- $X_s$ = variable reactance in series with the resonator used to vary the overall resonant frequency of the resonator-reactance combination

- $\phi$ = variable phase shifter used to force the oscillator signal frequency to change to a (new, 360° loop phase shift) frequency that varies within the resonator pass-band
## Oscillator Frequency Tuning

### Reactance Tuning
- Carrier signal is maintained at center of the transmission response of the resonator-reactance combination
- Impedance transformation is often required between the resonator and the tuning circuit

### Phase Shift Tuning
- Carrier signal moves within the resonator transmission response pass-band; tuning range is restricted to less than the passband width
- Phase shift circuit can be implemented as a 50 ohm device
- For electronic (voltage) tuning, the placement of the phase shift tuning circuit in the oscillator effects the sideband response of the oscillator, and must be taken into account in phase-locked oscillator applications
**Phase Shift Tuning**

Modulation frequency response affected by placement of phase shifter

Tuning voltage → delay = \( \tau \) → Resonator → A → \( \sum \) → sustaining stage

VCO Gain

- **actual gain constant**
- **desired gain constant = \( K_0/s \)**

modulation frequency

\[ 1/2\pi \tau \]
Methodology of Linear Frequency Tuning Using Abrupt Junction Varactor Diodes

- A resonator operated at/near series resonance exhibits a near-linear reactance vs frequency characteristic.

- Connection of a linear reactance vs voltage network in series with the resonator will then result in a circuit whose overall resonant frequency vs voltage characteristic is near-linear.

- The same holds true for a parallel connection of a parallel resonant resonator and a linear susceptance vs voltage circuit.

- Impedance transformation between the resonator and the tuning circuit is often required to increase tuning range using practical value components in the tuning circuit.

- Use of back-to-back varactor diodes in the tuning circuits has been found to eliminate effects of tuning circuit diode noise and oscillator signal spectral performance.
For abrupt junction varactor diodes, \( C = \frac{K}{(V+\phi)\gamma} \) where \( \phi = \) contact potential = 0.6 volts at room temp, and \( \gamma = 0.5 \)

To achieve near-linear reactance vs voltage using abrupt junction varactor diodes, \( \frac{1}{(L_pC_{vo})} = \omega_o^{2/3} \) where \( C_{vo} \) is the varactor diode capacitance at the band center voltage = \( V_o \)

For zero reactance at the band center tuning voltage, \( L_s = L_p/2 \)

The reactance vs voltage slope at the band center voltage is \( 0.375\omega_oL_p/(V_o+\phi) \)
For near-linear susceptance vs voltage using abrupt junction varactor diode, $\frac{1}{(L_s C_{vo})} = \omega_0^{2/3}$ where $C_{vo}$ is the varactor diode capacitance at the band center voltage = $V_o$

For zero susceptance at the band center tuning voltage, $C_p = C_{vo}/2$
## Linear Tunable Low Noise Oscillators: Typical Results

<table>
<thead>
<tr>
<th>Resonator Type</th>
<th>Tuning Range (ppm)</th>
<th>Error from Linear (ppm)</th>
<th>Tuning Circuit Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT-Cut Fundamental Quartz Crystal</td>
<td>2000</td>
<td>5</td>
<td>Reactance</td>
</tr>
<tr>
<td>AT-Cut Fundamental Quartz Crystal</td>
<td>250</td>
<td>1</td>
<td>Reactance</td>
</tr>
<tr>
<td>SC-Cut Overtone Quartz Crystal</td>
<td>10</td>
<td>0.5</td>
<td>Reactance</td>
</tr>
<tr>
<td>SAWR</td>
<td>500</td>
<td>5</td>
<td>Reactance</td>
</tr>
<tr>
<td>STW</td>
<td>500</td>
<td>100</td>
<td>Phase Shift</td>
</tr>
<tr>
<td>Coaxial Resonator Band pass Filter</td>
<td>150</td>
<td>50</td>
<td>Phase Shift</td>
</tr>
</tbody>
</table>
7. Environmental Stress Effects
Environmentally-Induced Oscillator Signal Frequency Change

- Resonator/Oscillator signal frequency change can be induced by changes in:
  - Temperature
  - Pressure
  - Acceleration (vibration)
  - Other (radiation, etc)
Vibration

Vibration constitutes the primary environmental stress affecting oscillator signal short-term frequency stability (phase noise).

Although resonator sensitivity to vibration is often the primary contributor, vibration-induced changes in the non-resonator portion of the oscillator circuit can be significant.

High Q mechanical resonances in the resonator and/or non-resonator oscillator circuitry and enclosure can cause severe signal spectral degradation under vibration.
Vibration: An Example

- A 100MHz crystal oscillator can exhibit a phase noise sideband level at 1KHz carrier offset frequency of -163dBc/Hz.
- The fractional frequency instability is $S_y(f=1000\text{Hz}) = 1 \times 10^{-26}/\text{Hz}$.
- The corresponding phase instability, $S_\phi(f)$, is $1 \times 10^{-16} \text{ rad}^2/\text{Hz}$.
- The crystal vibration level that would degrade the at-rest oscillator signal spectrum, based on a crystal frequency vibration sensitivity value $\Gamma_f = 5 \times 10^{-10}/\text{g}$ is quite small: $S_g(f) = S_y(f)/\Gamma_f^2 = 4 \times 10^{-8} \text{ g}^2/\text{Hz}$.
- The corresponding allowable signal path dimensional change, based on a wavelength of 300cm is: 48 angstroms/Hz$^{1/2}$.
- In the 50-ohm circuit, a capacitance variation (due to vibration-induced printed board or enclosure cover movement) of: $6 \times 10^{-7}$ pF/Hz$^{1/2}$ would degrade the at-rest signal spectrum.
Methods for Attenuating Effects of Vibration

- Vibration isolation of resonators or of entire oscillator
- Cancellation via feedback of accelerometer-sensed signals to oscillator frequency tuning circuitry
- Measurement of individual (crystal) resonator vibration sensitivity magnitude and direction and use of matched, oppositely-oriented devices
  - Use of multiple, unmatched oppositely-oriented devices
- Reduction of resonator vibration sensitivity via resonator design (geometry, mounting, mass loading, etc.)
“Poor Mans” Method for Reducing Quartz Crystal Vibration Sensitivity

- Two Crystals: partial cancellation in z and x directions, no cancellation in y direction

- Four Crystals: partial cancellation in x, y, and z directions

- Crystals connected electrically in series

- 5:1 reduction in vibration sensitivity magnitude has been achieved using four crystals
Measurement of Oscillator/Resonator Vibration Sensitivity

u Entire oscillator or resonator alone can be mounted on a shaker for determination of vibration sensitivity.

  l Resonator vibration sensitivity measurements can be made with the resonator connected to the oscillator sustaining stage or connected in a passive phase bridge.

u The effects of coaxial cable vibration must be taken into account, especially for measurement of devices having very small values of vibration sensitivity.

  l The effects of cable vibration can be determined by re-orienting the DUT on the shake table 180 degrees while not re-orienting the connecting coaxial cable and measuring the relative change in the magnitude and phase of the recovered, vibration-induced carrier signal sideband, relative to that of the shake table accelerometer.
Measurement of Oscillator/Resonator Coaxial Cable Affects

Measurement #1
Overall vibration sensitivity
\[ = \Gamma_{\text{COAX}} + \Gamma_{\text{DUT}} \]

Measurement #2
Overall vibration sensitivity
\[ = \Gamma_{\text{COAX}} - \Gamma_{\text{DUT}} \]
## Test Results for 40MHz Oscillator Sustaining Stage and Coaxial Cables

<table>
<thead>
<tr>
<th>Coaxial cable</th>
<th>50 ohm flexible coaxial cable</th>
<th>approx 15 micro-radians per g</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ohm semi-rigid coaxial cable</td>
<td></td>
<td>approx 5 micro-radians per g</td>
</tr>
</tbody>
</table>

| Sustaining Stage                  | Open loop measurements for a 2.5X2.5 inch PWB mounted on corners with no adjustable components | approx 1.5 micro-radians per g |

(vibration-induced phase shift increases with carrier frequency)
8. Oscillator Circuit Simulation and Noise Modeling
Small signal analysis is useful for simulating linear (start-up) conditions.

Simulation of steady-state condition is possible if/when large signal (i.e., in-compression) device s-parameters or ALC diode steady-state impedance values are known.

Circuit analysis/simulation should include component parasitic reactance (inductor distributed capacitance and loss, component lead inductance, etc). For circuits operating at and above VHF, printed board/substrate artwork (printed tracks, etc) should also be included in the circuit model.
Two port analysis is most appropriate for oscillator circuits employing modular amplifier sustaining stages. Open loop simulation in a 50 ohm system is valid for simulation of closed loop performance only when the loop is “broken” at a point where either the generator or load impedance is 50 ohms (i.e., at the amplifier input or output if the amplifier has good input or output VSWR).

One port (negative resistance generator) analysis is useful when simulating discrete oscillators employing transistor sustaining stage circuitry.
CAD circuit simulation can (and should) include circuit analysis at out-of-band frequency regions to make sure conditions for oscillation are only satisfied at the desired frequency.

Frequency bands where undesired resonator resonant responses occur (i.e., unwanted crystal overtone resonances) should be analyzed.

CAD circuit simulation results can be experimentally checked using an Automatic Network Analyzer (ANA).

Simulation also allows optimization of element values to tune the oscillator, as well as statistical analyses to be performed for determination of the effects of component tolerance.
Simulation of the Sustaining Stage Portion of a Crystal Oscillator

- Cx and Cy values optimized to provide $Z_{in} = -70 + j0$ at 100MHz

- $Z_{in}$ calculated from 50MHz to 1GHz to insure negative resistance is only generated over a small band centered at 100MHz (note use of $R_c$)

- Large signal condition (where the negative resistance portion of $Z_{in}$ drops to 50 ohms = crystal resistance) simulated by reducing the ALC impedance value

$Z_{in} = \text{impedance (negative resistance)}$

‘seen’ by the crystal resonator
100MHz Oscillator Sustaining Stage Circuit Simulation: 80MHz to 120MHz

\[ Z_{\text{in}} = -70 + j0 \text{ at } 100\text{MHz} \]
100MHz Oscillator Sustaining Stage Circuit Simulation: 50MHz to 1.5GHz

- 33 ohm collector resistor installed in the circuit
- Note that the real part of the impedance remains positive everywhere except at the desired frequency band at 100MHz
- This fact indicates the circuit will only oscillate at the desired frequency
Results of 100MHz Oscillator Sustaining Stage Circuit Simulation

- 50MHz to 1.5GHz; collector resistor (Rc) removed

- Note that the real part of the impedance becomes highly negative 1.15GHz

- This fact points to a probable circuit oscillation at/near 1.1GHz
Output signal near-carrier (1/f FM) noise primarily determined by crystal self noise.

TP1-to-TP2 voltage is maximized via trimmer capacitor adjustment. The voltage level is a measure (verification) of requisite loop excess gain.
80MHz Modular Amplifier Oscillator Circuit Simulation

- Open Loop Transmission Response: 79.998MHz to 80.002MHz
- Note that the excess gain is approximately 3dB
- The loaded Q of the crystal in the circuit is approximately 50,000
80MHz Oscillator Circuit Simulation

Effect of 5% tolerance in inductors and capacitors

- 99% of the time, the effect on open loop response is a phase shift off of nominal of less than 15 degrees (2.5ppm frequency error without circuit frequency adjustment)

- 90% of the time, the phase shift error is less than 10 degrees
Simple Oscillator Noise Modeling*  
(Open loop-to-closed loop method)

u Model the open loop noise of each functional sub-circuit (i.e., sustaining stage amplifier, tuning circuit, ALC/AGC circuit, and the resonator), usually as having a flicker-of-phase and a white phase noise component.

Steps:
1. Express the open loop noise of each component as a $S_f(f)/2$ noise power spectral density function of the form:

   $$10^{K_1/10}/f + 10^{K_2/10}$$

   $K_1 = 1\text{Hz} \times 1/f$ PM noise level, in dBc/Hz
   $K_2 = \text{white PM noise “floor” level, in dBc/Hz}$

Simple Oscillator Noise Modeling (cont.)

Steps, continued:

2. Add each of the noise power numeric values for the cascaded devices together.

2a. Also, apply the appropriate, normalized frequency-selective transmission responses (as a function of frequency offset from the carrier), including that of the frequency-determining element (i.e., resonator) to those component noises that are “filtered” by the responses along the signal path. In most cases, the transmission responses of the non-resonator circuits are broadband and are not included in modeling.
3. Calculate the oscillator closed loop signal PM noise sideband level as (for example):

\[ L(f) = 10 \log \left( \left( \frac{S_\phi_1(f)}{2} + \frac{S_\phi_2(f)}{2} \right) \left( H_a(f) \right) + \left( \frac{S_\phi_2(f)}{2} \right) \left( H_b(f) \right) + \frac{S_\phi_3(f)}{2} ... \right) \left( \frac{1}{2 \pi \tau} \right)^2 + 1) \]

- \( H(f) \) terms are the normalized transmission responses of frequency selective circuitry as a function of carrier offset (modulation) frequency, and \( \tau \) is the open loop group delay. The primary selectivity function and delay are those of the frequency determining element (resonator, multi-pole filter, delay line, etc).
- The \( \left( \frac{1}{2 \pi \tau} \right)^2 + 1 \) term accounts for the conversion of open loop phase fluctuations to closed loop frequency fluctuations in the oscillator.
Helpful Hints for Simple Oscillator Noise Modeling

The short-term frequency instability of the frequency-determining element can be modeled either as:

(a) having a open loop (normally flicker-of-phase) phase fluctuation spectrum that is then also “filtered” by the resonator transmission response, or

(b) a flicker-of-frequency fluctuation spectrum that is added separately to the calculated oscillator signal noise spectrum (not subject to the \((1/2\pi\tau)^2+1\) term).
Helpful Hints for Simple Oscillator Noise Modeling

The advantage of modeling the frequency-determining element instability as an open loop, phase fluctuation spectrum is that the spectrum used can be data collected from separate, phase bridge measurements of the phase instability induced onto a carrier signal by the device with corrections made for any differences in in-bridge vs in-oscillator circuit loading.
The vibration-induced noise can be modeled similarly by entering the vibration power spectral density function (including the transmission responses of vibration isolation systems used, unintentional mechanical resonances, etc), together with the frequency and/or phase sensitivities of the oscillator functional sub-circuits to vibration.

Normally, the most sensitive element is the resonator.

The vibration-induced PM noise is then simply added to the noise power numeric in the spreadsheet...either as vibration-induced, open loop phase instability spectrum (then converted with the other open loop noises to the closed loop noise) or as vibration-induced, resonator frequency instability spectrum added to the calculated oscillator closed loop noise.
Typical Plotted Result with Effects of Mechanical Resonance(s)

VHF Crystal Oscillator

- Mechanical resonance
- Isolator resonance

Graph showing PM Noise Sideband Level (dBc/Hz) vs Carrier Offset Frequency (Hz) with different noise sources:
9. Oscillator Noise
De-correlation/Noise Reduction Techniques
Methods to Reduce Noise Internal to the Oscillator Circuit

Use the resonator impedance or transmission response selectivity to reduce noise (i.e., extract the signal though the resonator to the load).

- Out-of-band noise suppression via:
  - Resonator transmission selectivity (RL) or
  - Resonator (high out-of-band) impedance selectivity (RL’)

- The technique shown above is not very useful for suppressing noise unless the output amplifier 1/f PM noise and noise figure are better than that of the sustaining stage amplifier
Methods to Reduce Noise Internal to the Oscillator Circuit (continued)

- Multiple, parallel sustaining stage amplifiers (amplifier 1/1 PM noise de-correlation)
- Multiple, series connected resonators (resonator 1/f FM noise de-correlation)
- Multiple resonators in an isolated cascade or multi-pole filter configuration (increased loop group delay)
Example: Multiple Device Use for Noise Reduction

- Noise de-correlation in amplifiers and/or resonators
- Cascaded amplifier-resonators to increase loop group delay
Additional Methods for Reducing Noise Internal to the Oscillator Circuit

Consider sustaining stage amplifier noise reduction via:

- noise detection and base-band noise feedback (to phase and amplitude modulators) or
- feed-forward noise cancellation
**Example: Noise Reduction Techniques**

- Wide-band noise feedback to reduce sustaining stage amplifier $1/f$ PM noise
- VHF delay $= \tau$
- Double frequency conversion:
  - Sustaining stage implementation at VHF using a low $1/f$ PM noise amplifier
**Example:**

**Additional Noise Reduction Techniques**

Use of resonator response to increase phase detector sensitivity

(JPL and Raytheon)

Carrier nulling with post-nulling uwave amplifier used to increase phase detector sensitivity

(Univ. Western Australia/Poseidon Scientific Instruments)
Advantages of Noise Feedback in X-Band, Sapphire Dielectric Resonator (DR) Oscillators

- Lower Noise with 60 times lower Q

![Graph showing phase noise sideband level vs. carrier offset frequency for different oscillators.]

- Northrop Grumman Oscillator using double frequency conversion sustaining stage and low order mode DR at 77K, Q=350,000 (1995 IEEE FCS)
- Hewlett Packard Oscillator using no noise feedback and high order mode DR at 28K, Q=20 million (1993 IEEE FCS)
- PSI Oscillator using high sensitivity noise feedback and high order mode DR at 300K, Q=200,000 (1996 IEEE FCS)
Amplifier Noise Reduction via Feed-forward Cancellation*

(no noise down-conversion to base-band)

*amplifier operated linearly

---

- **Input signal**: f
- **Power divider**
- **Power combiner (nuller)**
- **Post-null amplifier**
- **1/f noise introduced by amplifier**
- **1/f noise cancelled (subtracted out)**
- **Noise enhancement**: carrier nulled, but 1/f noise not nulled
Methods to Reduce Noise External to the Oscillator Circuit

- External active (phase-locked VCO) or passive, narrow-band spectral cleanup filters
- Overall subsystem noise reduction via feedback or feed-forward noise reduction techniques
**UHF VCO Phaselocked To HF Crystal Oscillator:**

- Oscillator noise reduction can be accomplished via external filters:
  - passive filter
  - phase-locked oscillator
- Provides near-carrier noise of HF crystal oscillator plus low noise floor of UHF VCO (PLL BW APPROX. 5KHz)

![Graph showing PM Noise Sideband Level vs. Carrier Offset Freq](image-url)
Overall Subsystem Noise Reduction using a Discriminator

- Large delay needed to obtain high detection sensitivity
- Large delay implies high delay line loss and/or small resonator bandwidth
- Can achieve similar noise levels by using the same, high delay device in a microwave oscillator
10. Oscillator Test and Troubleshooting Methods
Steps:

1. Measure one-port negative resistance vs frequency using Automated Network Analyzer (ANA) s11 measurements (may need to use a series build-out resistor to keep the sustaining stage from oscillating).

2. For the closed loop (oscillating circuit), measure the circuit nodal voltage amplitude and relative phase and view the amplitude waveforms to estimate the degree of limiting (excess gain) using a vector voltmeter or similar test equipment.
Steps, continued:

3. If the circuit does not oscillate, break open the oscillator loop where accurate duplication of source and load impedances is not critical (i.e., where $Z_S$ is much smaller than $Z_L$ and drive the circuit with an external generator to determine ‘faulty’ portion of the circuit from phase and amplitude measurements made along the signal path.

4. As necessary, make circuit modifications to achieve desired circuit open loop phase and gain characteristics.

Note:
In-circuit resonator effective Q can be determined by intentionally altering the circuit phase shift by a known amount and measuring the resultant oscillator signal frequency shift.
Example: Test Set Up

Z_{in}(Q1) > Z(C1)

20KHz sampled outputs

- Signal Generator
- Vector Voltmeter
- Scope

(Q1) > Z(C1)
Modular Amplifier Sustaining Stage
Oscillator Test and Troubleshooting

Steps:

1. Break open the oscillator loop at a point where the circuit impedance is close to 50 ohms (either on the generator or load side).

2. Using an Automated Network Analyzer (ANA), measure the transmission response (s21 phase and amplitude) to verify adequate excess gain and the response centered at the zero degree phase frequency.

2a. Increase the ANA drive until steady-state drive conditions are achieved (gain drops to unity). The sustaining stage amplifier input is the recommended signal insertion point.
Modular Amplifier Sustaining Stage

Steps, continued:

3. As an alternative, the loop can be opened and driven from a signal generator, and relative signal amplitude and phase measurements made along the circuit signal path using vector voltmeter probes.

4. As necessary, make circuit modifications to achieve desired circuit open loop phase and gain characteristics.
**Typical Display of Network Analyzer Data**

- Example: ANA Measurement of 100MHz Crystal Oscillator
- Small and Large Signal Open Loop Response: $s_{21}$ magnitude

- Small Signal Gain: +2.6dB
  (ANA Po=AMP 11dBm - 11dB = 0 dBm)

- Large Signal (Steady State) Gain: 0 dB
  (ANA Po=8 dBm)
Typical Display of Network Analyzer Data

- Example: ANA Measurement of 100MHz Crystal Oscillator
- Small and Large Signal Open Loop Response: s21 angle

![Diagram showing small and large signal phase responses.](image-url)
11. Summary
Designing the Optimal Oscillator

- Identify the oscillator/resonator technology best suited for the application
  - Operating frequency
  - Unloaded Q
  - Drive level
  - Short-term stability
  - Environmental stress sensitivity
**Designing the Optimal Oscillator**

- Identify the optimum sustaining stage design to be used
  - Discrete transistor
  - Modular amplifier
  - Silicon bipolar, GaAs, HBT, etc.
  - ALC, AGC, or amplifier gain compression

- Determine if use of noise reduction techniques, including multiple device use, noise feedback, feed-forward noise cancellation, vibration isolation, etc is needed
Verify Oscillator Design

- Perform CAD circuit analysis/simulation
- Know or measure the resonator short-term frequency stability
- Know or measure the sustaining-stage 1/f PM noise at operating drive level
- Know or measure the resonator and non-resonator circuit vibration sensitivities and package mechanical
The Optimal Oscillator: ‘Wish List’ for Future Improvements

- Improvements in resonator performance
  - New resonator types having higher Q, higher drive capability, higher frequency, smaller volume, better short-term stability, and lower vibration sensitivity

- Microwave (sustaining stage) transistors/amplifiers with lower levels of 1/f AM and PM noise
  - New semiconductor designs, materials, processing
  - Circuit noise reduction schemes (feedback, etc)

- Improved vibration sensitivity reduction schemes
  - Cancellation, feedback control, mechanical isolation, etc.
12. List of References
1. Short-term Frequency/Phase/Amplitude Stability


2. Basic Oscillator Operation


3. Types of Resonators and Delay Lines


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4. Useful Network/Impedance Transformations


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5. Sustaining Stage Design and Performance

5-1. W. A. Edson, *Vacuum Tube Oscillators*, John Wiley and Sons, N.Y., 1953


7. Environmental Stress Effects


8. Oscillator Circuit Simulation and Noise Modeling

9. Oscillator Noise De-correlation/Reduction Techniques


