Low Noise Oscillator Design and Performance

Michael M. Driscoll

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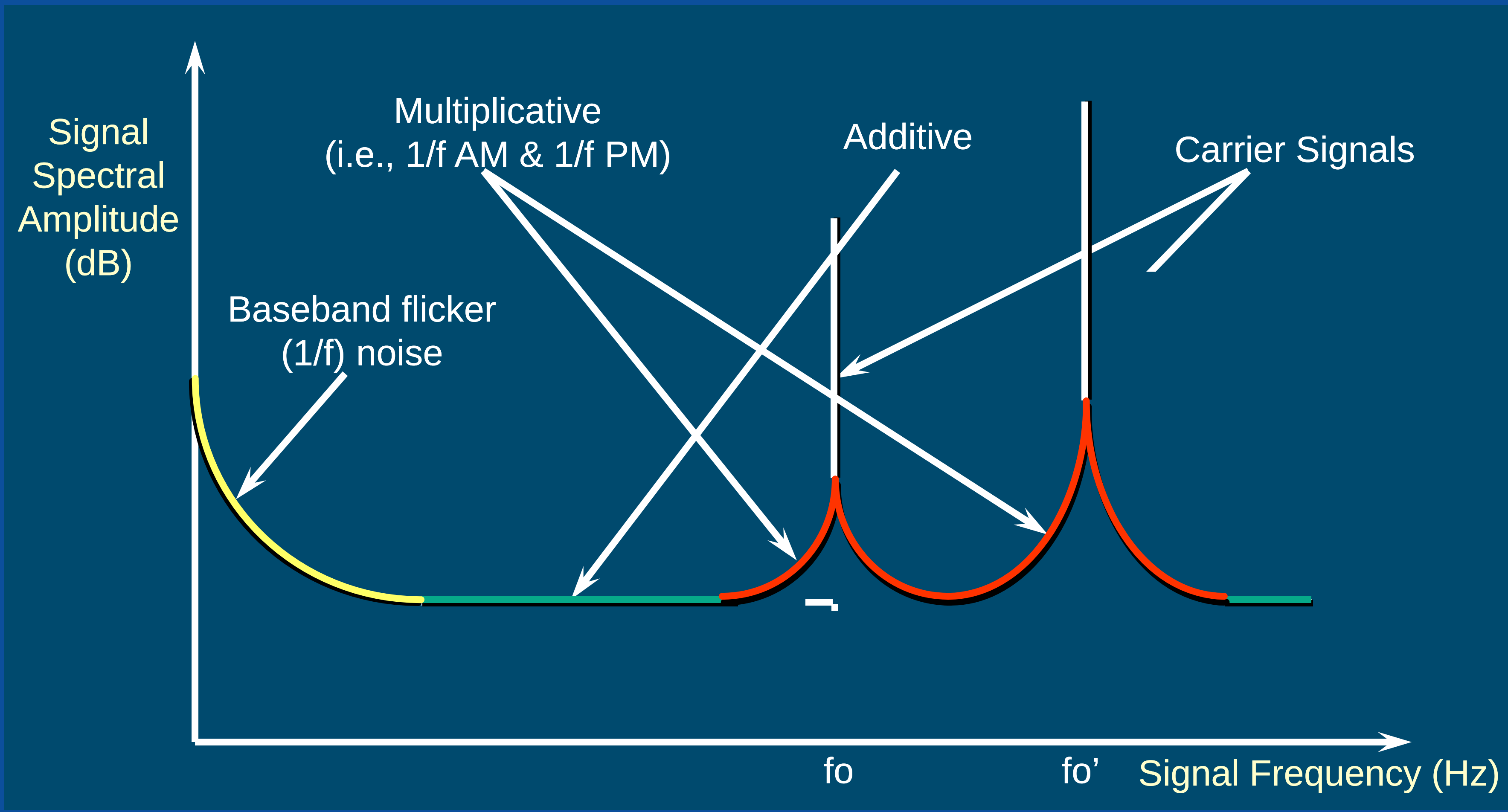
1. Short-term Frequency/Phase/ Amplitude Stability

Types of Phase and Amplitude Noise



Additive Noise (independent of signal level)

- Amplifier additive noise level is related to the input signal level, the amplifier noise figure, the device temperature.
- Amplifier input noise power ¯ KTBF ¯-174dBm/Hz + F(dB)

  where K=Boltzman's constant, T=300K, B=bandwidth = 1Hz, and F=noise figure.
- Carrier signal-to-noise ratio (dBc/Hz)   -174 + F(dB)   Psignal (dBm)
- Since ½ noise is AM and ½ is PM, the Carrier-signal-to-PM noise ratio is -177 + F(dB) – Psignal (dBm).
- If/when the amplifier is operated at/near gain compression, the "additive" (i.e., white) noise level can increase by several dB.

Characteristics of Multiplicative Noise

- Multiplicative noise is <u>not</u> independent of carrier signal level.
- 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 trans-conductance (gm) or the 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.

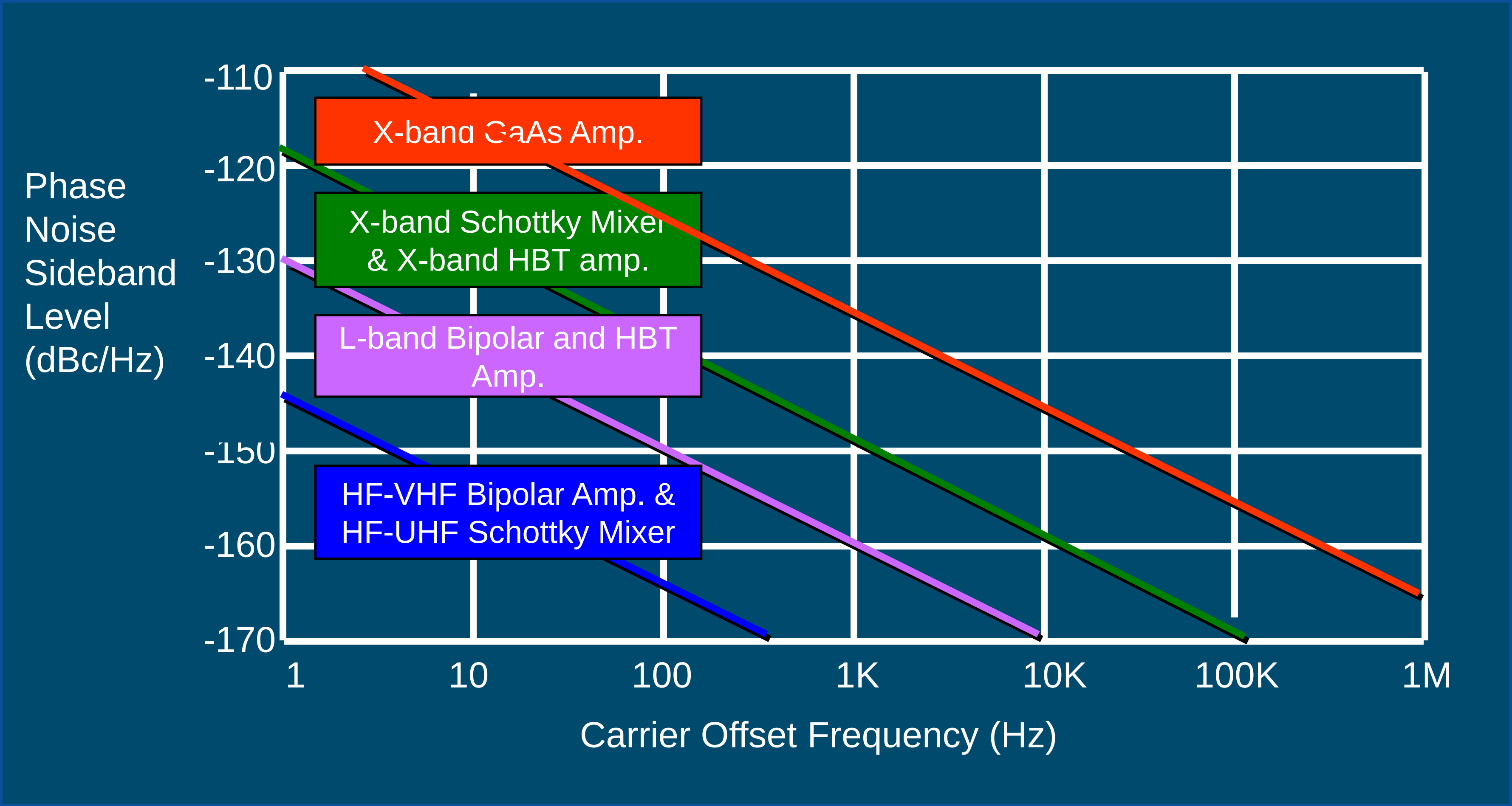
Characteristics of Multiplicative Noise (continued)

- 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 low1/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 enough purchased/sample devices to yield statistical data.
- In an oscillator, amplifier 1/f PM noise is converted to higher level 1/f FM at carrier offset frequencies less than $1/2\pi\tau$, where τ is the open loop delay, primarily due to the resonator.

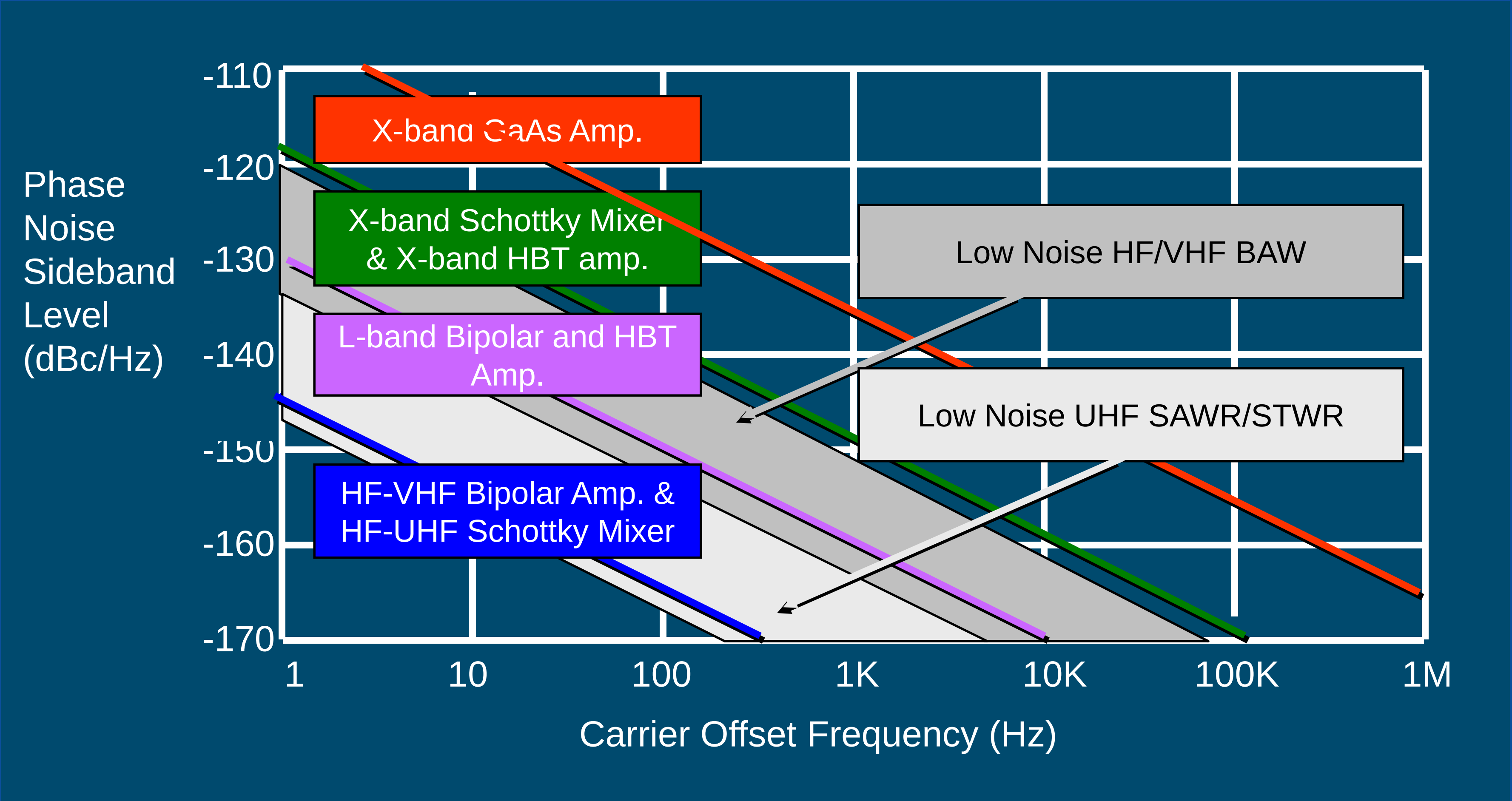
"Typical" Semiconductor Component 1/f PM Multiplicative Noise Levels



"Passive" 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 (but are usually not) comparable to or higher than to that of the sustaining stage amplifier 1/f AM and PM noise.
- The oscillator frequency control element (i.e., resonator) can exhibit dominant levels of flicker-of-resonant <u>frequency</u> instability, <u>especially acoustic resonators.</u>
- In an <u>open loop</u> sense, the resonator instability can be plotted as flicker-of-<u>phase</u> noise (induced on a carrier signal passing through the resonator).

Resonator Open Loop Phase Instability



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Commonly Used Measures of Oscillator Signal Short-Term Frequency Stability

- Time Domain: $\sigma_y(\tau)$ = Two sample deviation (square root Allan Variance)

$$\sigma_y(\tau) = ½ (y_{k+1} - y_k)^{2}>$$

- Frequency Domain:

$\mathcal{L}(f) = 10LOG (S_\phi(f)/2)$

For small modulation indices, $\mathcal{L}(f)$ = single sideband phase noise-to-carrier power ratio in a 1Hz bandwidth at a offset frequency f from the carrier (dBc/Hz)

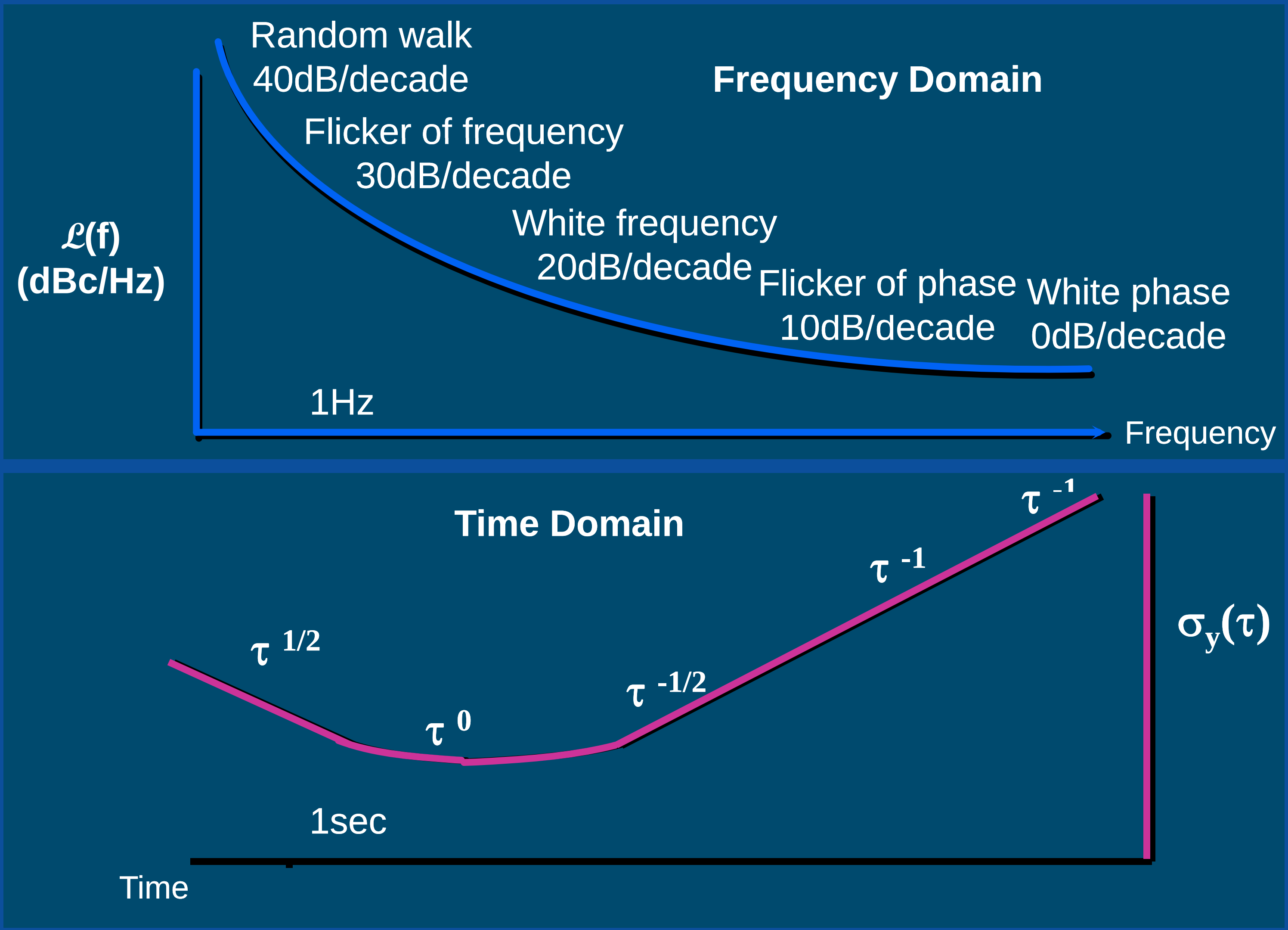
$S_\phi(f)$ = Spectral density of the phase fluctuations (rad^2/Hz).

$S_y(f)$ = Spectral Density of the fractional frequency fluctuations (1/Hz).

$S_y(f) = (f/\nu_o)^2 S_\phi(f)$, $\mathcal{L}(f) = 10LOG(S_\phi(f)/2)$

ν_o = carrier frequency

Types of Frequency/Phase Noise Spectra



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Conversion from Frequency to Time Domain

- 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

$$\mathcal{L}(f) \text{ indBc/Hz} = 10LOG(S_\varphi(f)/2) = 10LOG[(\frac{\nu_0}{f})^2 Sy(f)/2$$

ν_0 = carrier frequency

f = fourier frequency

$S_y(f) = H_\alpha f^\alpha$ α =	$S_y(f) = a\,\sigma_y(t)$ a =
2 (white phase)	$((2\pi)^2 \tau^2 f^2)/(3f_h)$
1 (flicker noise)	$((2\pi)^2 \tau^2 f^2)/(1.038+3/n(\omega\tau))$
0 (white frequency)	2τ
-1 (flicker frequency)	$1/((2f)/n(2))$
-2 (random walk frequency)	$6/(2\pi)^2 \tau f^2$

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Example: Conversion from Frequency to Time Domain

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

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

Then Sy(f) in the same region

$$= (10^{\mathcal{L}(f)/10})2f/\nu_o = (10^{-12})(200/10^8)=2X10^{-22}/f$$

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

$\sigma_y^2(\tau)$ in the region

τ = 1/f = 1sec = (2)(ln(2))(Sy(f))(f) = 2.77X10-22

therefore, $\sigma_y(\tau)$ = 1.66X10-11

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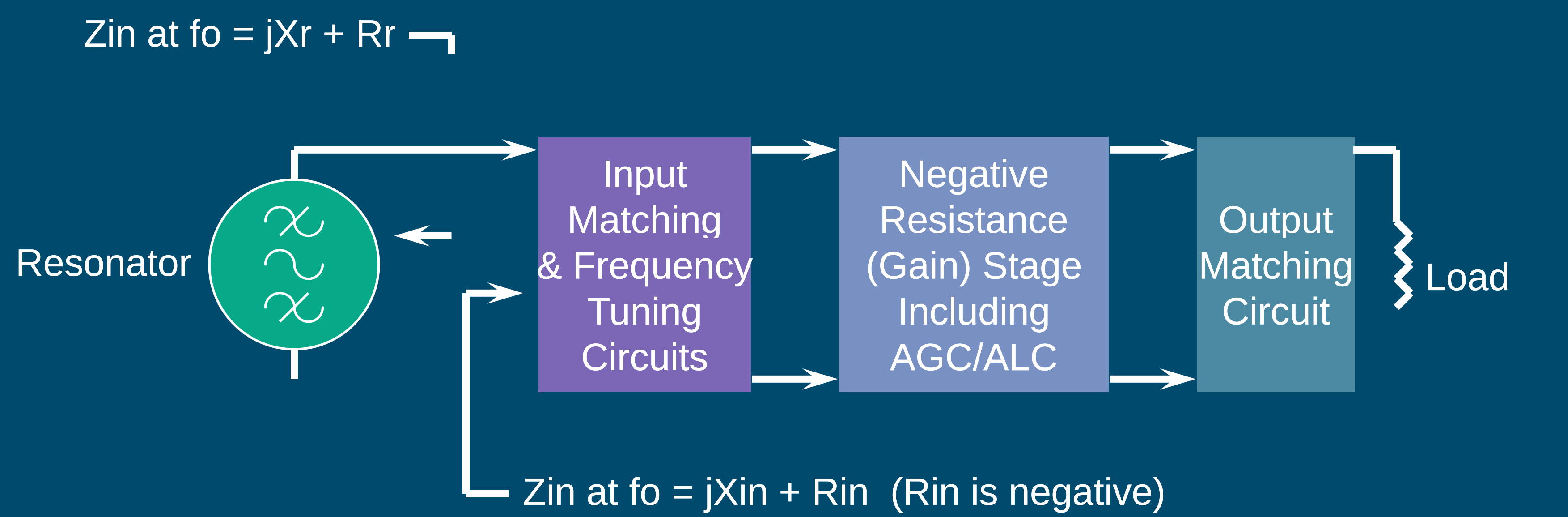
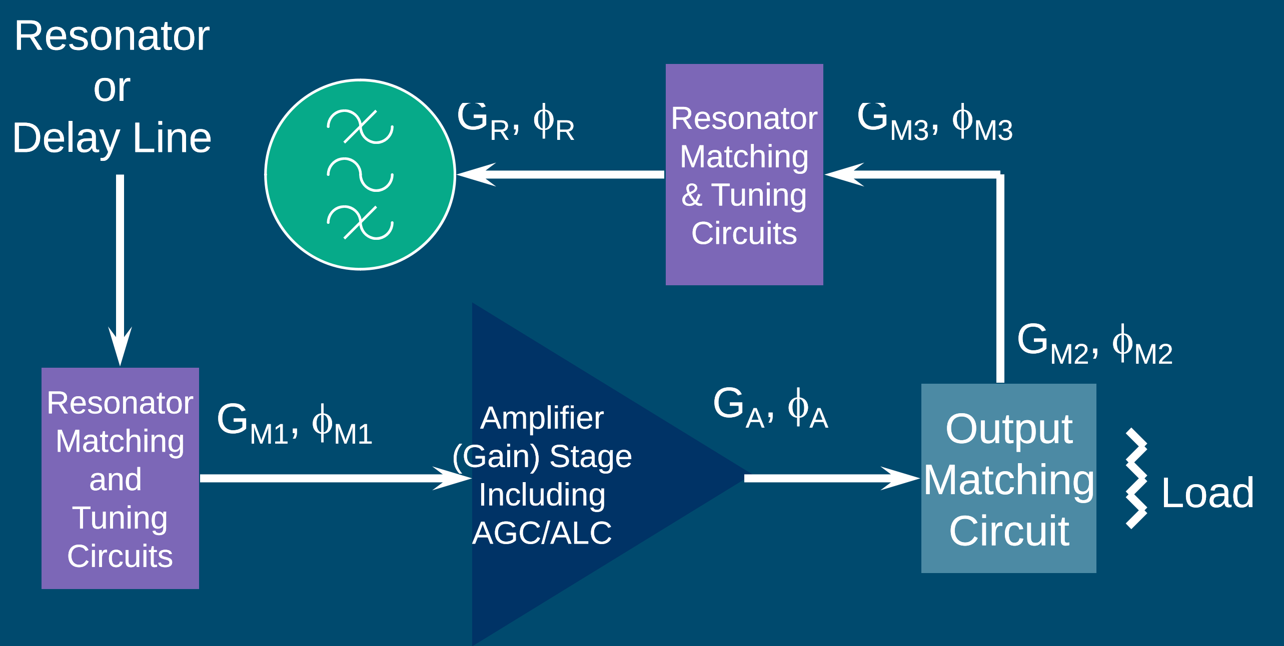
2. Basic Oscillator Operation

Oscillator Viewed as a Two Terminal Negative Resistance Generator



Conditions for start-up: Xr = -Xin, Rr + Rin< 0
Steady State: -Xin, Rr + Rin = 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

ALC / AGC Must Occur

- Types of automatic level control (ALC) and/or automatic gain control (AGC):

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

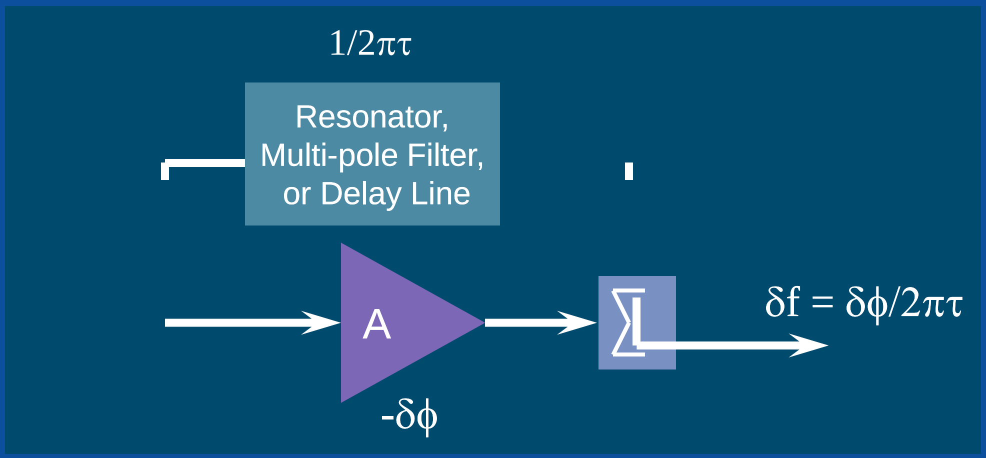
  (2) Gain reduction using a feedback control loop. The oscillator RF signal is DC-detected, and the amplified detector output fed to a variable gain control element (i.e., PIN attenuator) in the oscillator.

*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

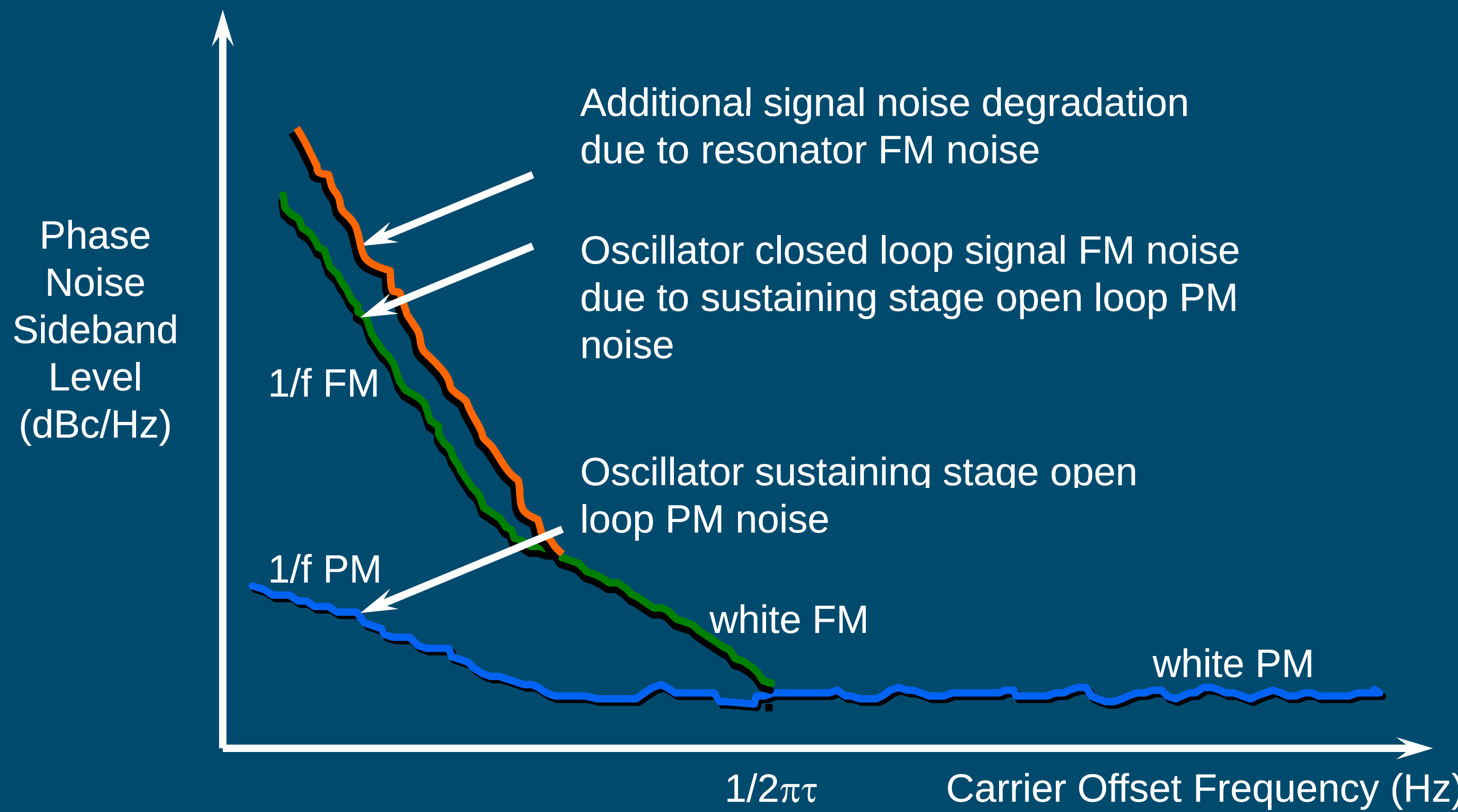
Conversion of Phase to Frequency Instability in an Oscillator



- 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 ($2n\pi$ 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 τ is the loop group delay ($1/2\pi\tau$ = BW/2 for a single resonator).
- The conversion process can be described by:

  Closed-loop $S_\phi(f)$ = open-loop $S_\phi(f)((1/2\pi\tau f)^2+1)$

PM-to-FM Noise Conversion in an Oscillator



τ = oscillator closed loop group delay
1/2πτ = BW/2 for a single (1 pole) resonator

Characteristics of "Ideal" Resonator

- High group delay (high resonator loaded Q)
- For microwave signal generation: high operating frequency
- Low loss
- Moderately high 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
- Low cost: 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 the ALC/AGC circuits or in the amplifier itself when operated in gain compression
- 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: high manufacturing yield of acceptable devices

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 vibration sensitivity
- Relatively low cost
- Moderately small volume (especially SAW, STW)
- Well defined, mature technology

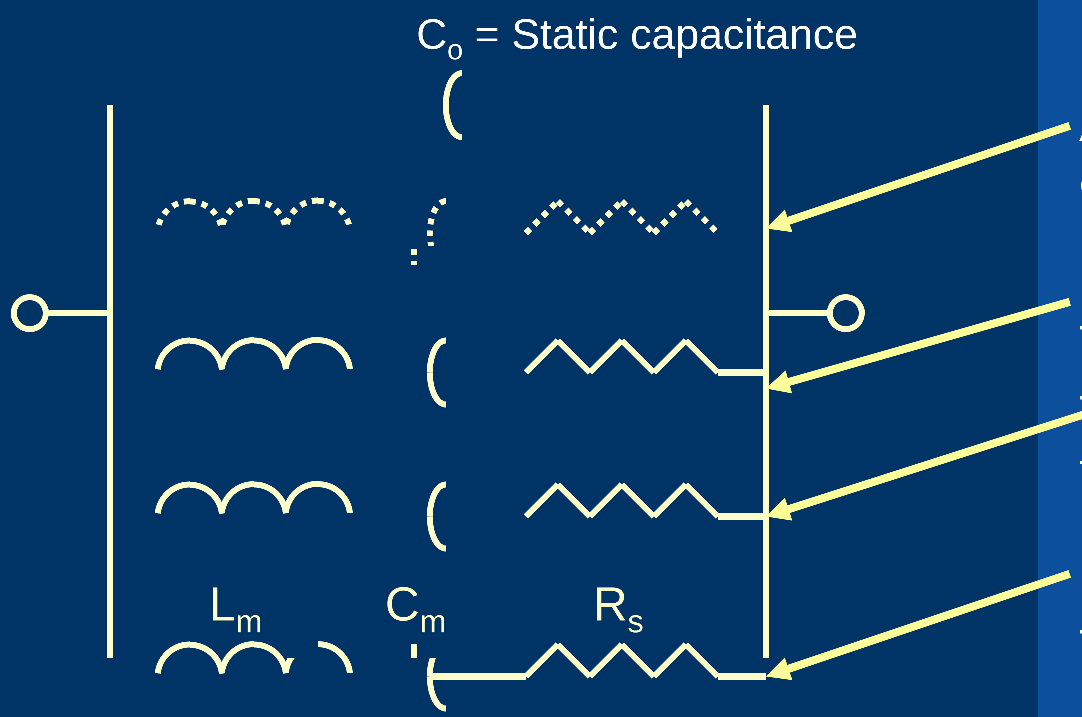
Undesirable Properties

- 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 Acoustic Resonators, continued

Quartz Crystal Electrical Equivalent Circuit

(for widely used AT-cut and SC-cut crystals)



Anharmonic and higher, odd-overtone resonance(s)

Fifth overtone resonance, f approx $5f_s$

Third overtone resonance, f approx $3f_s$

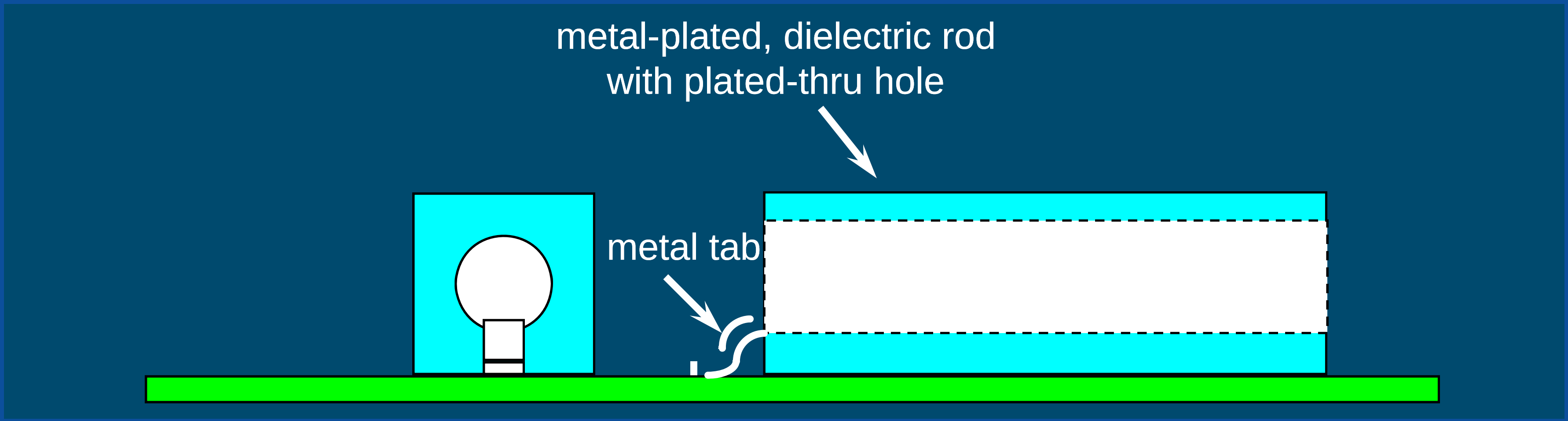
Fundamental resonance, $f_s=1/(2\pi(LmCm)^{0.5})$

- L_m = motional (series) inductance
- C_m = motional capacitance
- R_s = series resistance $2\pi f_s/R_s$ = unloaded Q

Improvements in Acoustic Resonator Performance - 1985 to 1999

Year	Resonator Type	Frequency	Noise Level, Sy(f=100Hz) Nominal	Noise Level, Sy(f=100Hz) Best	Pmax (mW)	Virbration Sensitivity (parts in 10^{-10}/g)
1985	5th OT AT-cut	80MHz	$1.5X10^{-24}$	$3X10^{-25}$	2	5 to 20
1985	Raytheon SAW	500MHz	$5X10^{-25}$	$1X10^{-25}$	50	5 to 50
1989	5th OT AT-cut	40MHz	$2X10^{-25}$	$4X10^{-26}$	2	10 to 30
1989	3rd OT SC-cut	80MHz 100MHz	$5X10^{-25}$	$1X10^{-25}$	7	3 to 10
1995	5th OT SC-cut	160MHz	$1X10^{-25}$	$2X10^{-26}$	7	3 to 10
1995	SAWTEK STW	1000MHz	$5X10^{-24}$	$1X10^{-24}$	100	1 to 3
1999	FEI OT SC-cut	100MHz	???	$2X10^{-26}$	???	???

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)
- $\mathcal{L}$(100Hz)=-100dBc/Hz, with -178dBc/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 Resonator Use 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

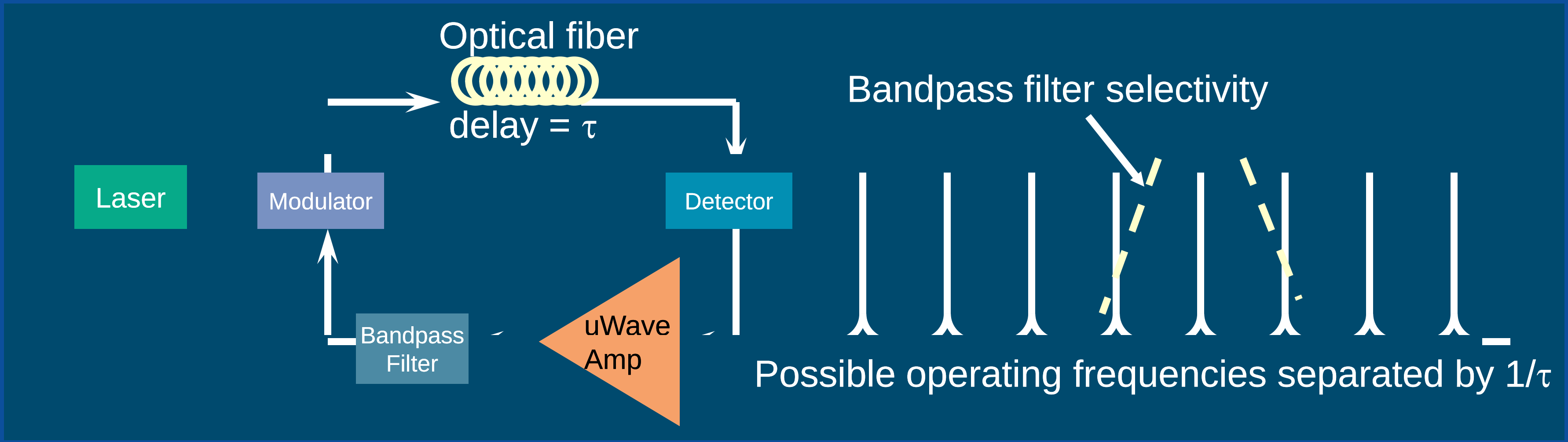
Advantages

- High delay possible: tens of microseconds
- Low optical signal strength loss in fiber
- Opto-electronic Oscillator (OEO) signal generation directly at microwave
- Near-carrier noise level (i.e., set by the delay) is “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
- RF amplifier 1/f PM noise levels are <u>not</u> independent of carrier frequency
- For low noise signal generation, long fiber length results in conditions for oscillation being satisfied at multiple, closely-spaced frequencies requiring a high Q, RF filter to select the desired frequency
- Selectable (reciprocal of delay) frequencies are non-coherent

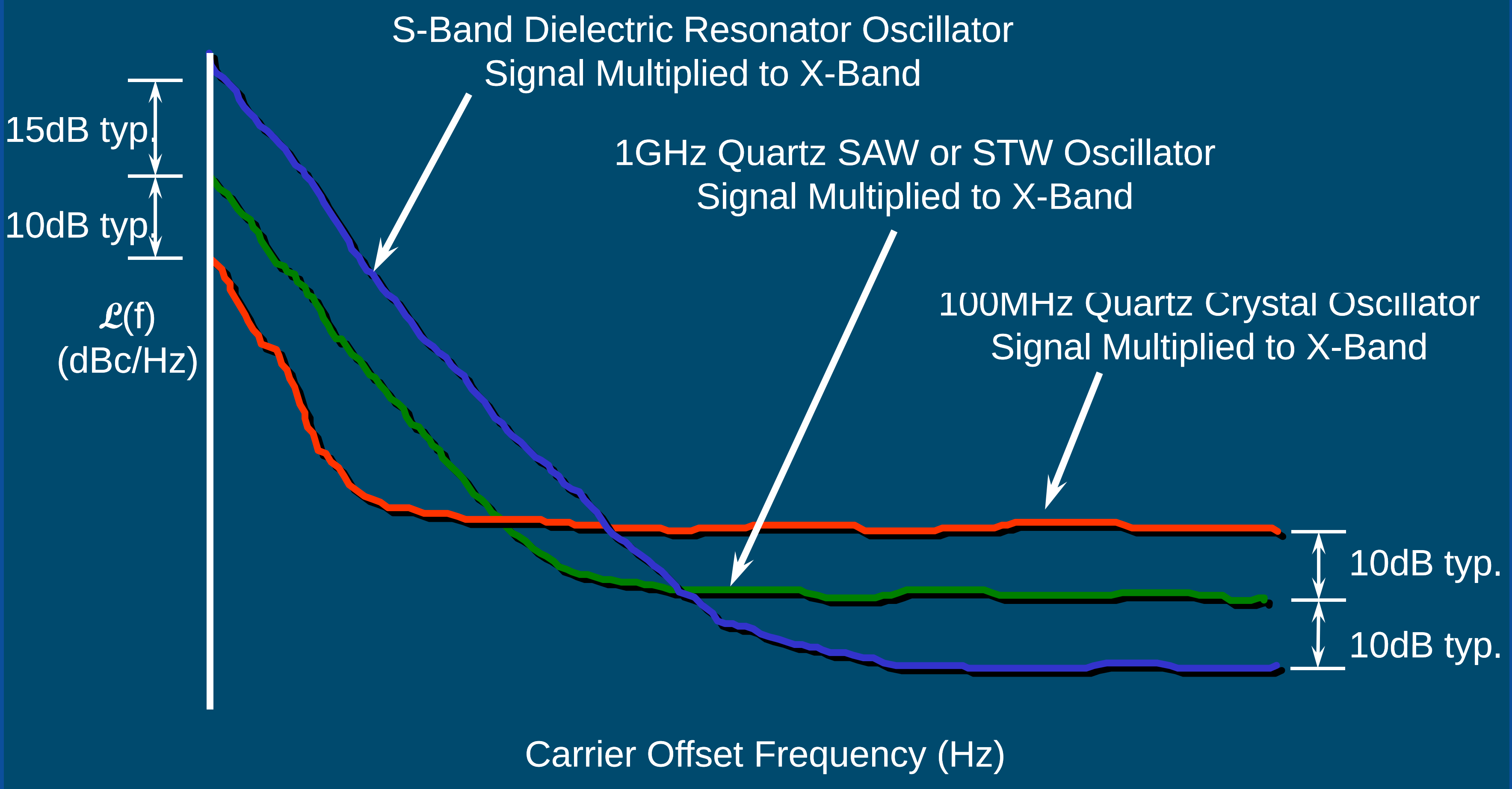
Opto-Electronic Oscillator (OEO)



- 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 a quartz crystal oscillator signal or SAW oscillator signal, frequency multiplied to microwave.

Reference: JPL:1995-1999 Freq. Contr. Symp.

Spectral Tradeoff: Near-Carrier vs Noise Floor Performance



NOTE: The plots do not differ by 20LOG(frequency ratio) because the loaded Q values and drive level capability associated with each resonator technology are different.

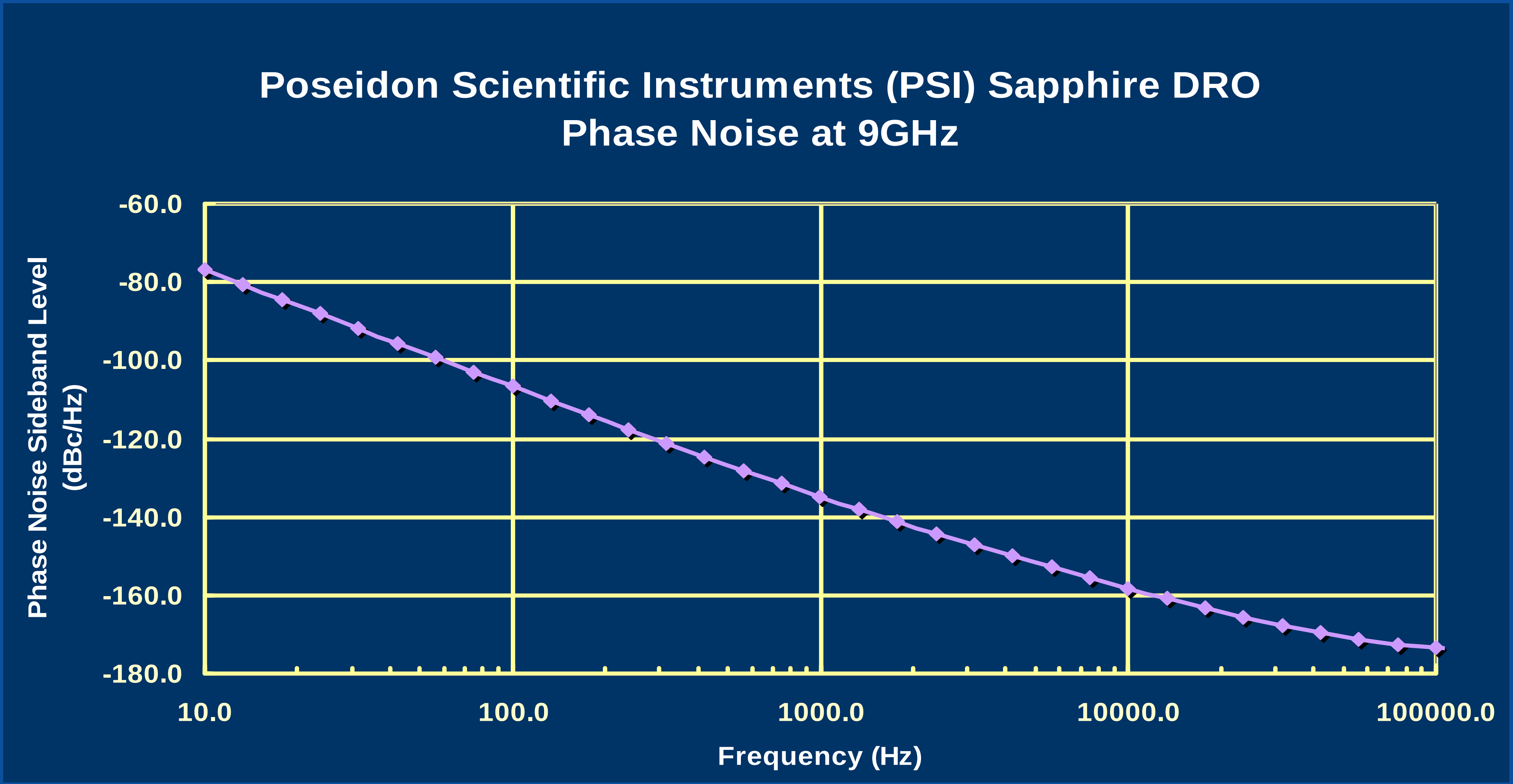
Whispering Gallery Mode, Sapphire Dielectric Resonators

- Dielectric loss in sapphire is very 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 10million at liquid nitrogen temperature.
- This ultra-high resonator Q results in oscillators whose X-band output signal spectra are currently 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 lower 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



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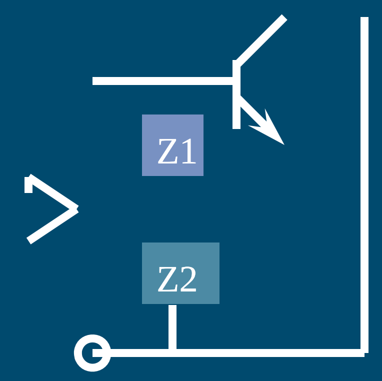
4. Sustaining Stage Design and Performance

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

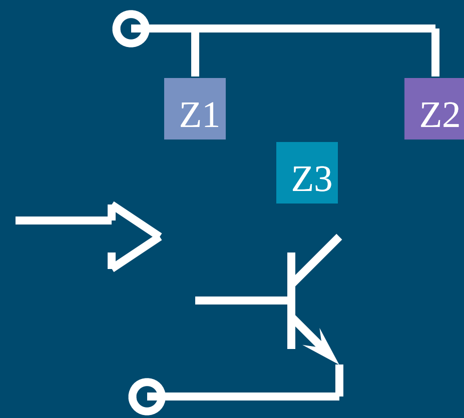
Zin (ideal voltage-controlled current source)
= Z1 + Z2 + gm(Z1)(Z2)
If Z1 and Z2 are reactances, Z1=jX1, Z2=jX2, and
Zin = j(X1+X2) -gm(X1)(X2)
where -gm(X1)(X2) is the negative resistance term



- Normally, capacitors are used for the reactances X1 and X2.
- 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 ωo)

Zin (ideal voltage-controlled current source)
= (Z1)(Z2)/(Z1+Z2+Z3) + 1/gm
If Z1=1/jωC1, Z2=1/jωC2, and Z3=jωLs+Rs
and if, at $\omega = \omega_o$, Z1/Z2/Z3 are resonant
(Z1+Z2+Z3 − Rs),
then Zin at $\omega = \omega_o = -1/(\omega_o^2 C1C2Rs) + 1/gm$

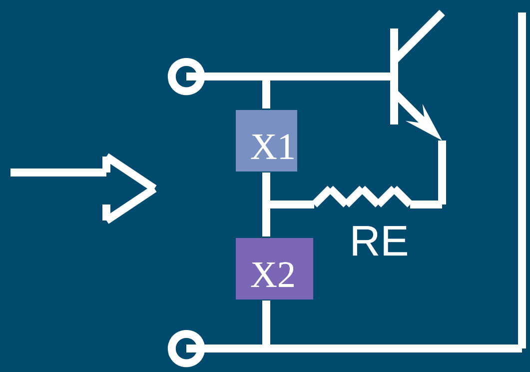


- Normally, capacitors are used as the impedances Z1 and Z2.
- Z3 is normally an inductor, and the net resonant resistance of the series combination = Rs, includes that portion of Rs due to the the circuit external load resistance as well as the loss in the inductor.

Use of Unbypassed Emitter Resistance for Gain (Negative Resistance) Stabilization

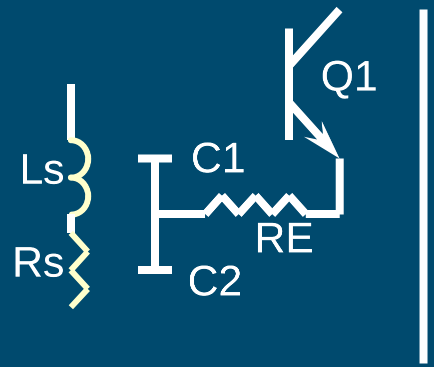
Zin = j(X1+X2) - (X1)(X2)/(RE+1/gm)

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

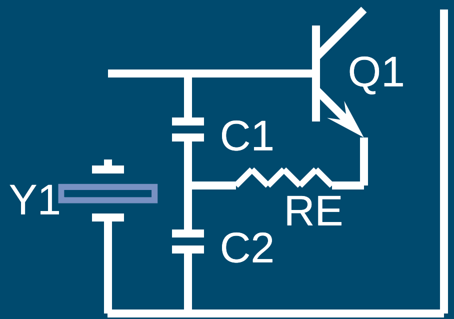


- The addition of RE stabilizes the negative resistance (makes it more dependent on RE then on gm.
- In addition, un-bypassed emitter resistance constitutes one method for reducing transistor 1/f PM noise levels.

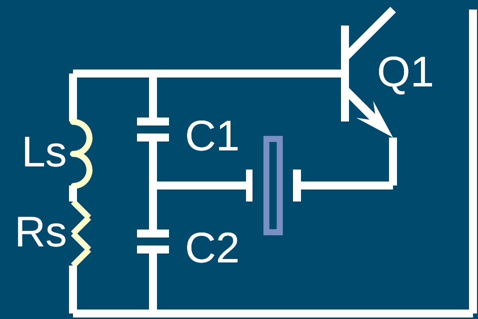
Crystal Oscillators with Crystal Placement in Different Portions of the Circuit



basic oscillator circuit



crystal operation above fs
where Z_{Y1} = $j\omega Ls + Rs$



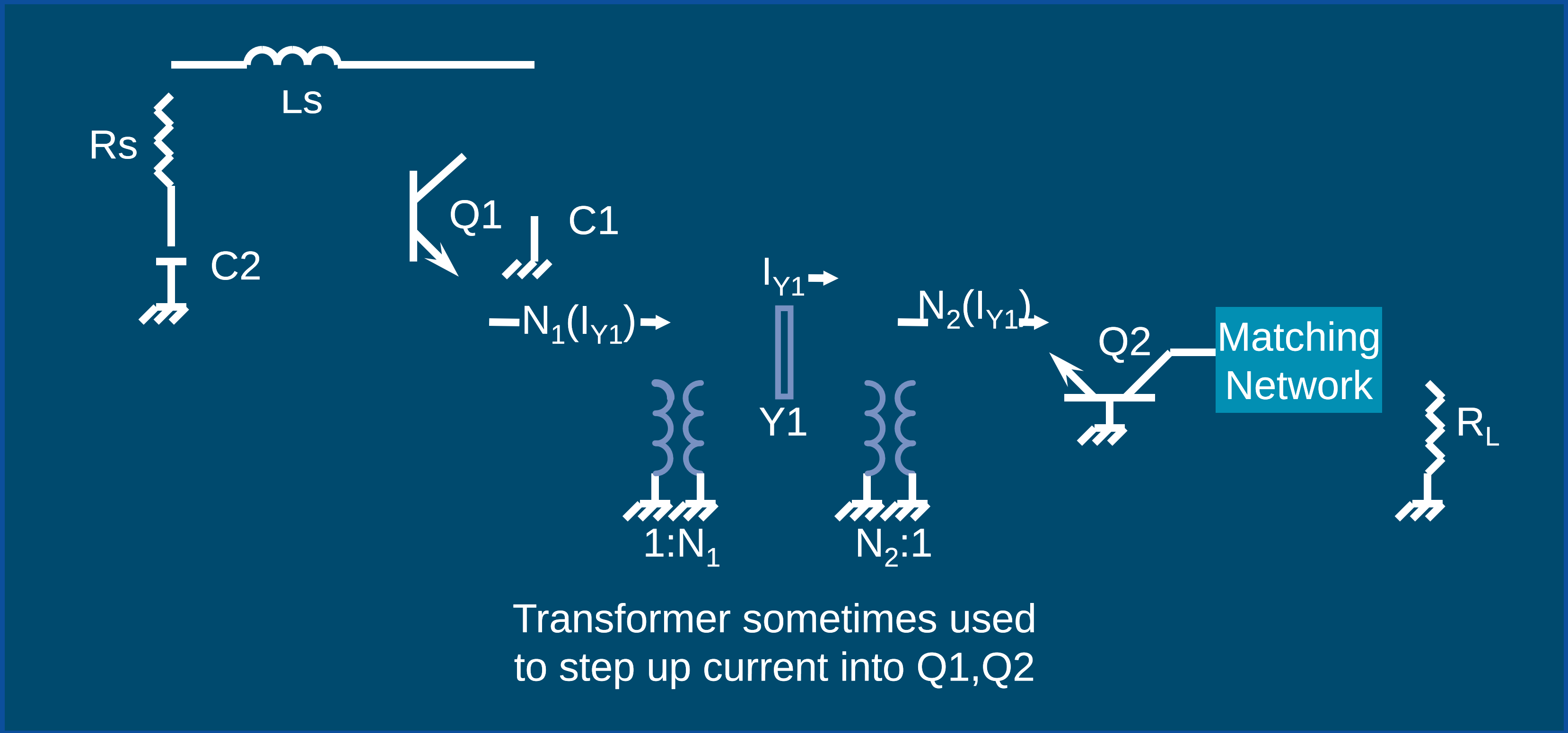
crystal operation at fs
where Z_{Y1} = Rs (i.e., Z=RE)

Methods for Reducing Discrete Transistor Sustaining Stage 1/f PM Noise

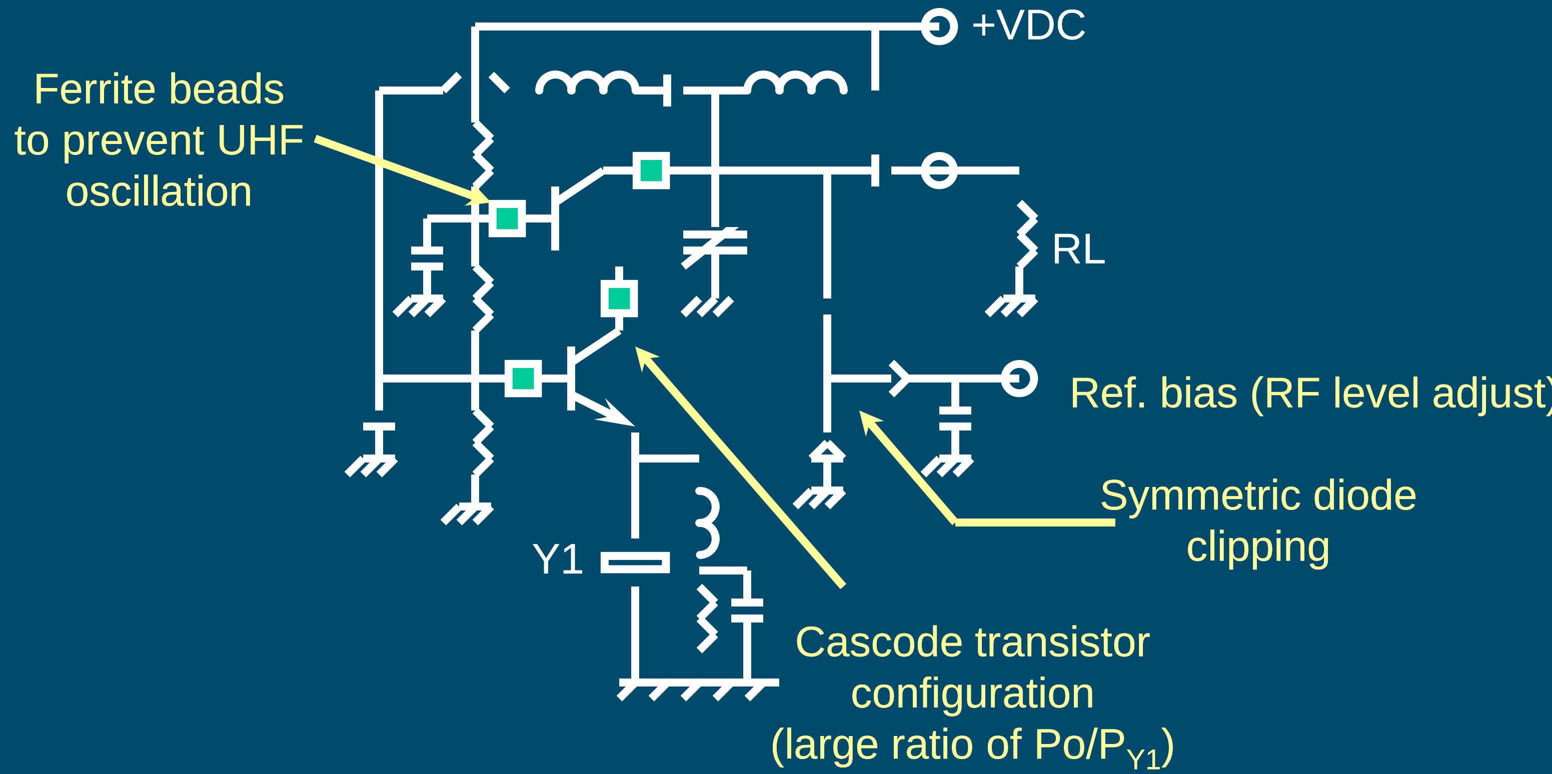
- Use un-bypassed emitter resistance (a resistor or the resonator itself connected in series with the emitter.
- Use high frequency transistors having small junction capacitance and operated at moderately high bias voltage to reduce phase modulation due to junction capacitance noise modulation*.
- Use 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



Discrete Transistor Oscillator Example: Low Noise, VHF Crystal Oscillator



Discrete Transistor Sustaining Stages

Advantages

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

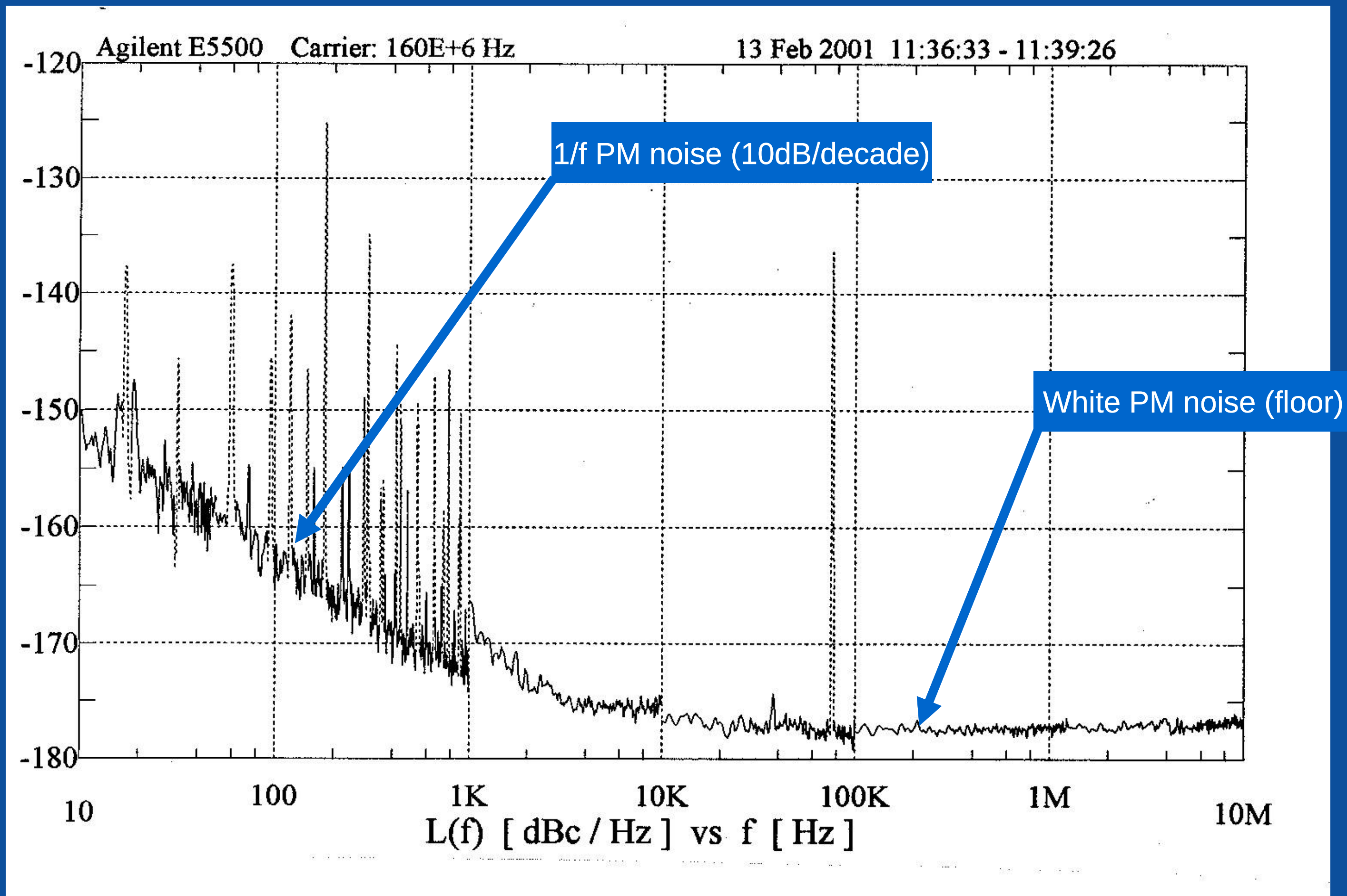
Disadvantages

- For low noise, transistors with high ft 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

- Amplifiers are 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 the possibility of parasitic oscillations.
- Amplifiers are 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



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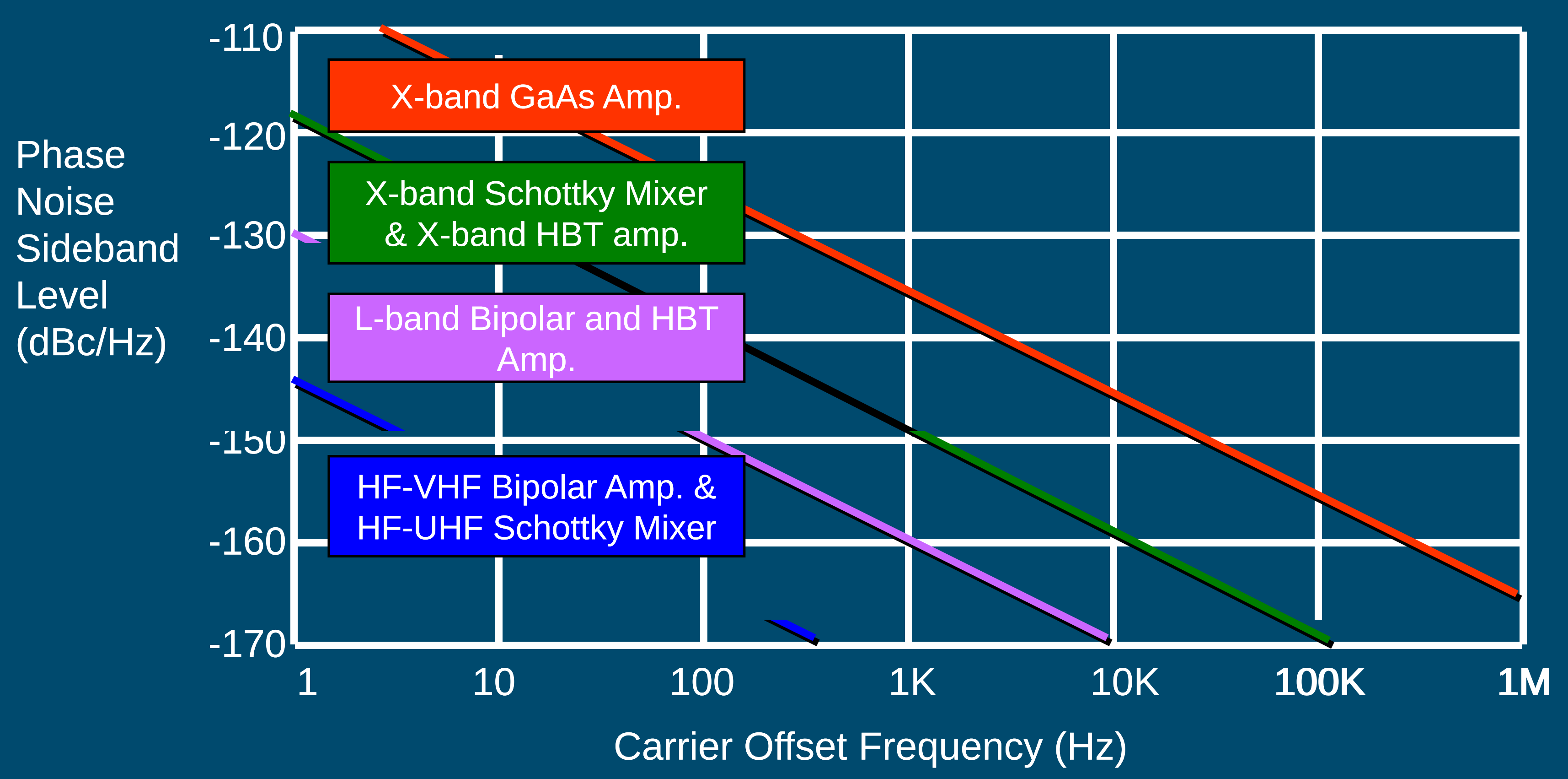
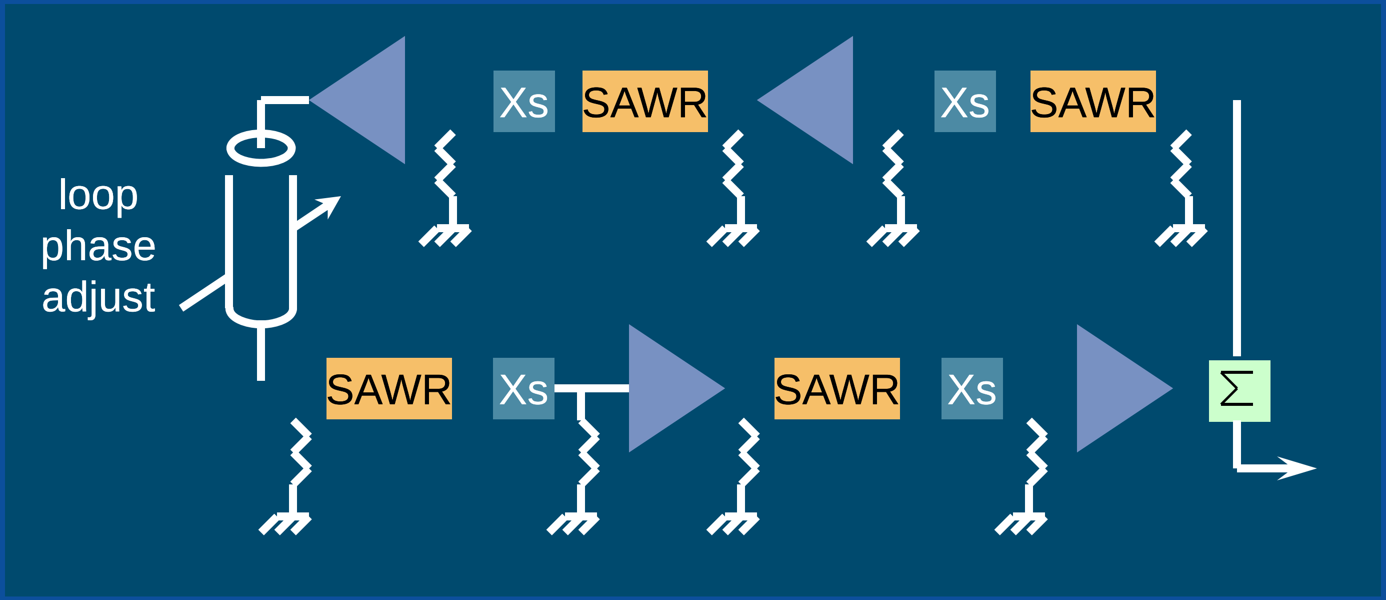
“Typical” Component 1/f PM Multiplicative Noise Levels



Modular Amplifiers: General Comments

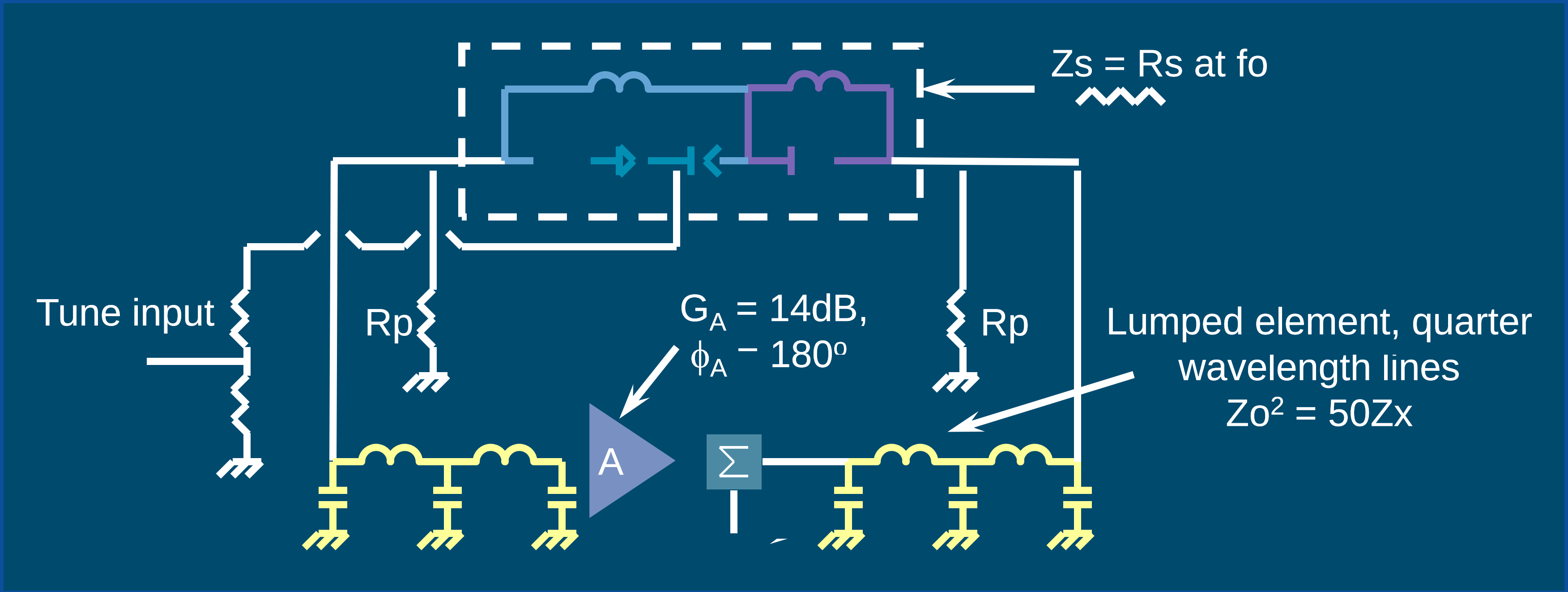
- Generally, amplifier vendors do not design for, specify, or measure device 1/f AM and PM noise.
- It is usually necessary to evaluate candidate sustaining stage amplifiers in terms of measured 1/f AM and PM noise at intended drive level (i.e., in gain compression when the oscillator will not employ separate ALC/AGC).
- Amplifier S21 phase angle sensitivity to gain compression, as well as gain magnitude and phase sensitivity to DC supply voltage 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.
- The evaluation must be performed on a large enough quantity of devices to gain accurate insight into statistical variations in 1/f PM noise level.

Modular Amplifier Oscillator Design Example: Low Noise, SAWR Oscillator



- Xs is a select-in-test inductor or capacitor to align SAWR center frequency.
- Four, cascaded combinations of SAWRs and amplifiers were used to increase loop group delay.
- We achieved -124dBc/Hz at fm=100Hz at fo=320MHz.
- The technique requires accurate tracking between resonators over time and temperature.

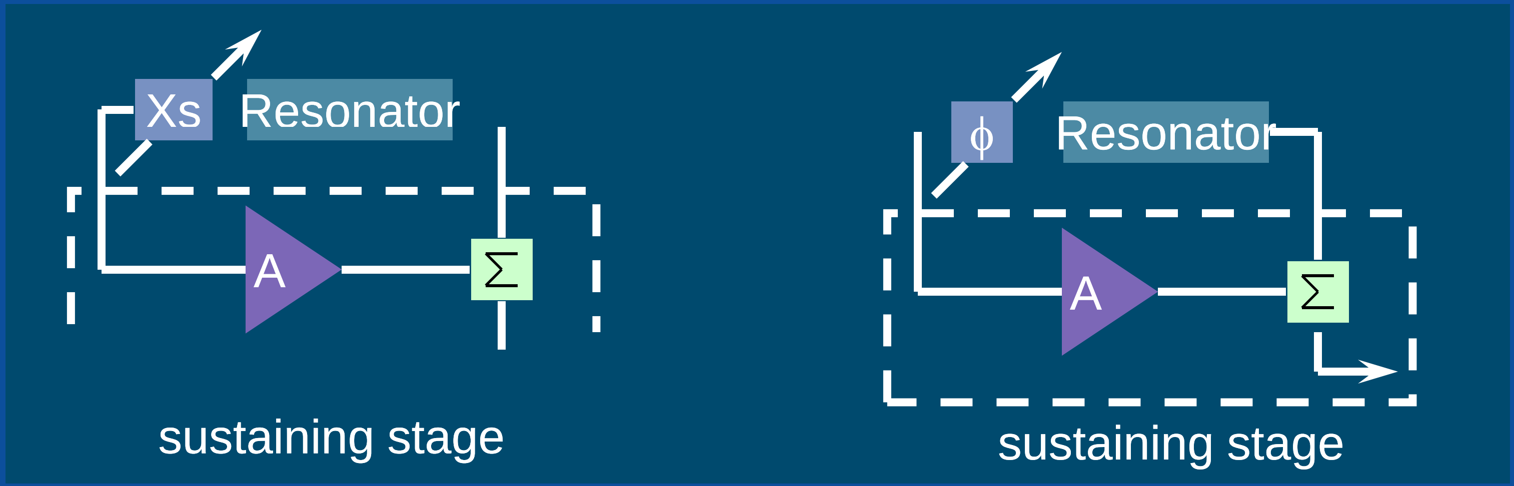
Modular Amplifier Oscillator Design Example: Low Noise, HF Oscillator



- The net, series resistance of the crystal + varactor-inductor tuning circuit, act in combination with parallel (Rp) resistors, like a “pad” whose characteristic impedance is Zx.
- The two, quarter-wavelength lines yield 90º phase shift each and match 50 ohms to Zx at fo, provide improper phase shift below fo and attenuation above fo, thereby preventing oscillation at other crystal resonant modes.
- Demonstrated performance: -156dBc/Hz at fm=100Hz at fo=10MHz using third overtone AT-cut crystals.

5. Oscillator Frequency Adjustment/Voltage Tuning

Methods for Providing Oscillator Frequency Tuning



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

- ϕ = variable phase shifter used to force the oscillator signal frequency to change to a (new, 360º 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

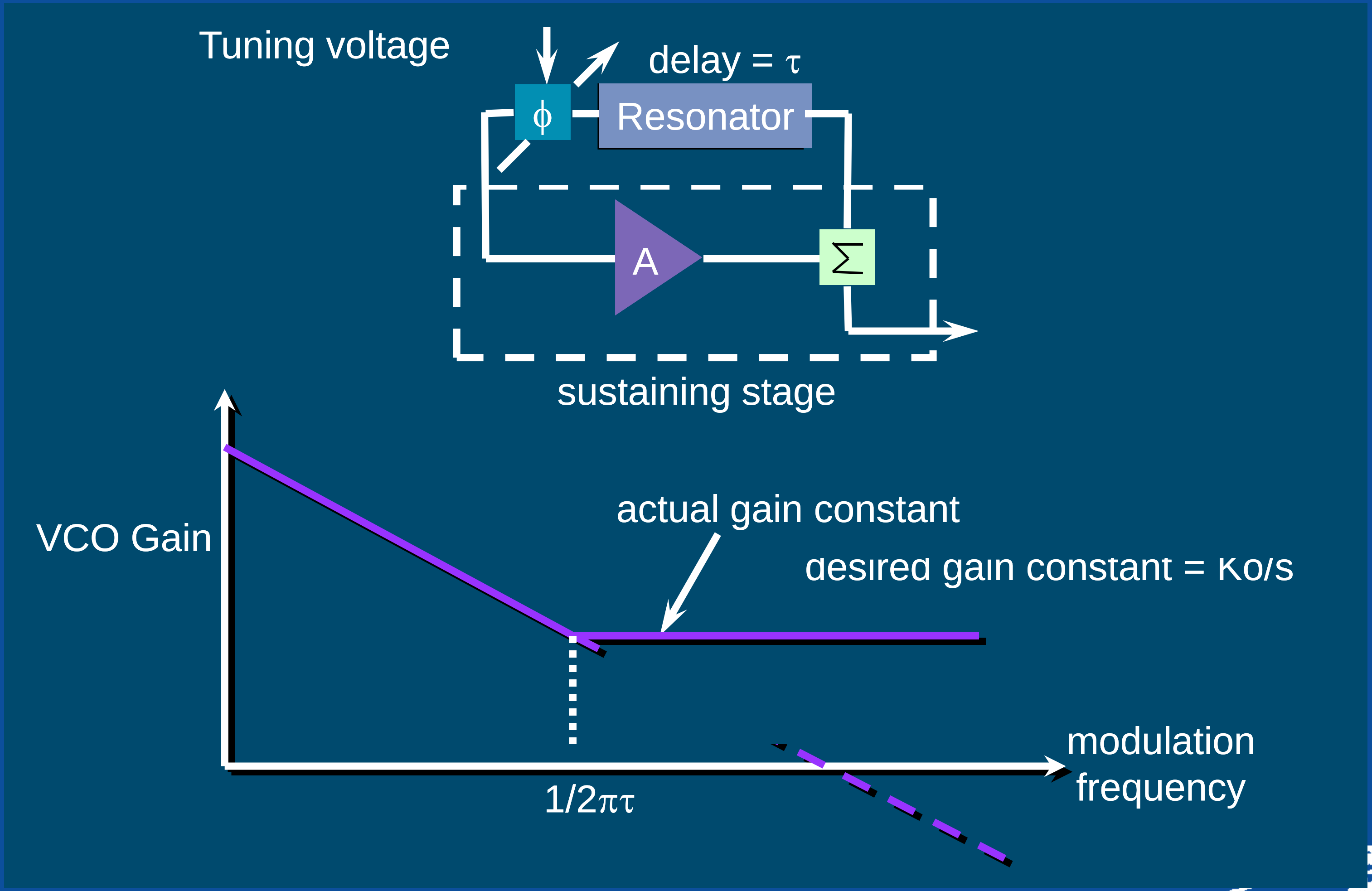
Carrier signal moves within the resonator transmission response pass-band; tuning range is restricted to less than the passband width.

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

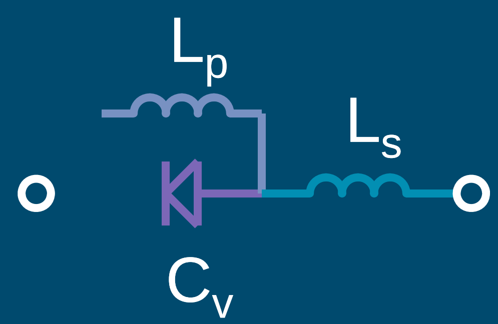
- Modulation frequency response affected by placement of phase shifter



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 n oscillator signal spectral performance.

Obtaining Linear Reactance vs Voltage



- For abrupt junction varactor diodes, $C = K/(V+\phi)^{\gamma}$ where ϕ = contact potential 0.6 volts at room temp, and γ 0.5
- To achieve near-linear reactance vs voltage using abrupt junction varactor diodes, $1/(LpCvo) = \omega_o^2/3$ where Cvo is the varactor diode capacitance at the band center voltage Vo
- For zero reactance at the band center tuning voltage, Ls=Lp/2
- The reactance vs voltage slope at the band center voltage is $0.375\omega_o Lp/(vo+\phi)$

Linear Tunable Low Noise Oscillators: Typical Results

Resonator Type	Tuning Range (ppm)	Error from Linear (ppm)	Tuning Circuit Type
AT-Cut Fundamental Quartz Crystal	2000	5	Reactance
AT-Cut Fundamental Quartz Crystal	250	1	Reactance
SC-Cut Overtone Quartz Crystal	10	0.5	Reactance
SAWR	500	5	Reactance
STW	500	100	Phase Shift
Coaxial Resonator Band pass Filter	150	50	Phase Shift

6. 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.
- Non-linearities (surfaces “hitting” under vibration) can create phase noise at frequencies in excess of the maximum vibration frequency.

Vibration: An Example

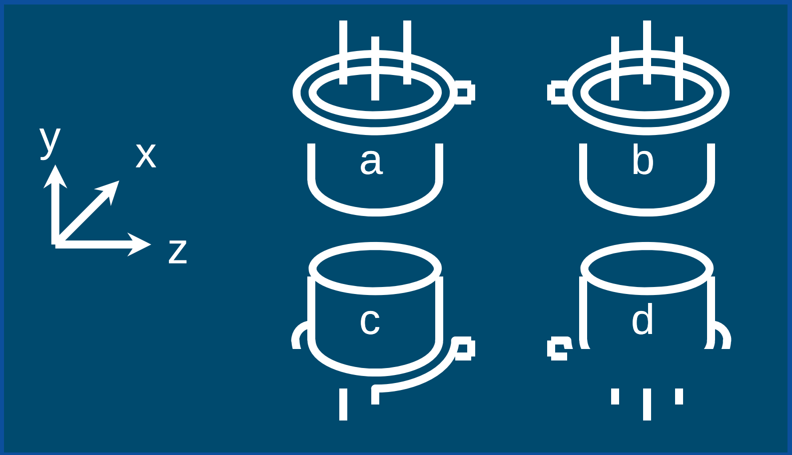
- A 100MHz crystal oscillator can exhibit a phase noise sideband level at 1KHz carrier offset frequency of -163dBc/Hz.
- The fractional frequency instability is Sy(f=1000Hz) = $1X10^{-26}$/Hz.
- The corresponding phase instability, $S\phi(f)$, is $1X10^{-16}$ rad^2/Hz.
- The crystal vibration level that would degrade the at-rest oscillator signal spectrum, based a crystal frequency vibration sensitivity value $\Gamma_f = 5X10^{-10}$/g is quite small: Sg(f) = $Sy(f)/\Gamma_f^2 = 4X10^{-8}$ g^2/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: $6X10^{-7}$ 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 vie feedback of accelerometer-sensed signals to oscillator frequency tuning circuitry or to the (SC-cut crystal) resonator
- 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

- The entire oscillator or resonator alone can be mounted on a shaker for determination of vibration sensitivity.
  - Resonator vibration sensitivity measurements can be made with the resonator connected to the oscillator sustaining stage or connected in a passive phase bridge.
- The effects of vibration in the coaxial cable connections from the DUT on the shaker to the stationary, measurement apparatus must be taken into account, especially for measurement of devices having very small values of vibration sensitivity.

Test Results for 40MHz Oscillator Sustaining Stage and Coaxial Cables

Coaxial cable

50 ohm flexible coaxial cable	approx 15 micro-radians per g
50 ohm semi-rigid coaxial cable	approx 5 micro-radians per g

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)

7. Oscillator Circuit Simulation and Noise Modeling

CAD Small Signal Analysis/Simulation of Oscillator Circuits

- 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.

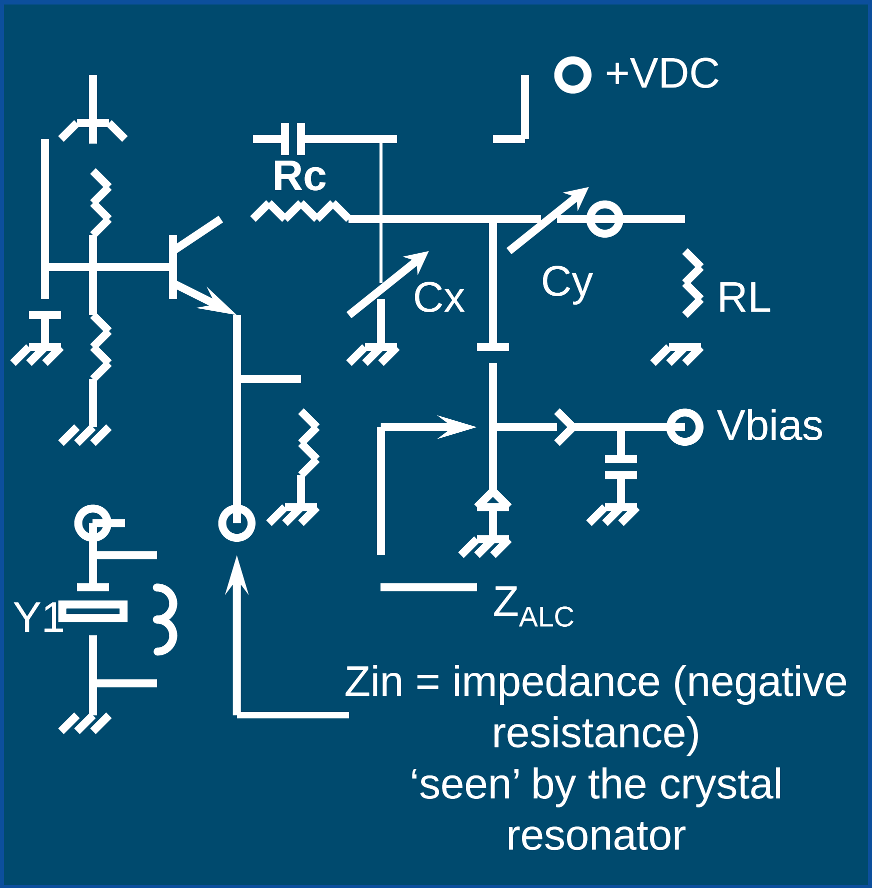
CAD Small Signal Analysis of Oscillator Circuits

- 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 Small Signal Simulation of Oscillator Circuits

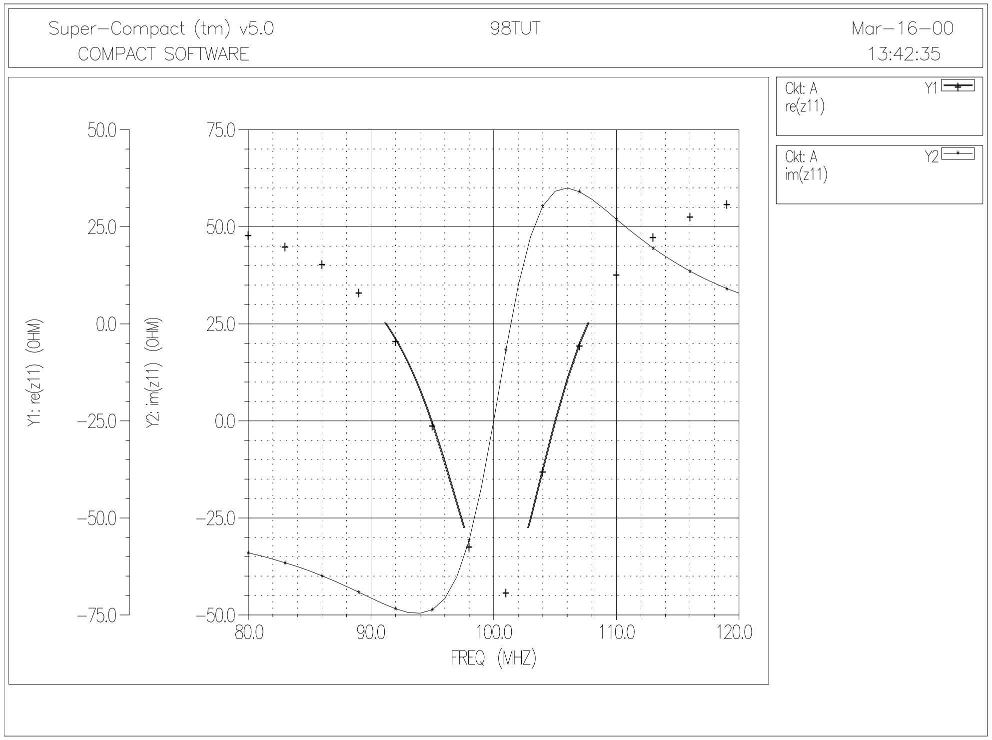
- CAD circuit simulation can (and should) include circuit analysis at out-of-band frequency regions to make sure conditions for oscillation are only satisfied at the desired frequency.
- Frequency bands where undesired resonator resonant responses occur (i.e., unwanted crystal overtone resonances) should 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 Zin = -70 + j0 at 100MHz.
- Zin calculated from 50MHz to 1GHz to insure negative resistance is only generated over a small band centered at 100MHz (note use of Rc).
- Large signal condition (where the negative resistance portion of Zin drops to 50 ohms = crystal resistance) simulated by reducing the ALC impedance value.

100MHz Oscillator Sustaining Stage Circuit Simulation: 80MHz to 120MHz



- Zin = - 70 + j0 at 100MHz

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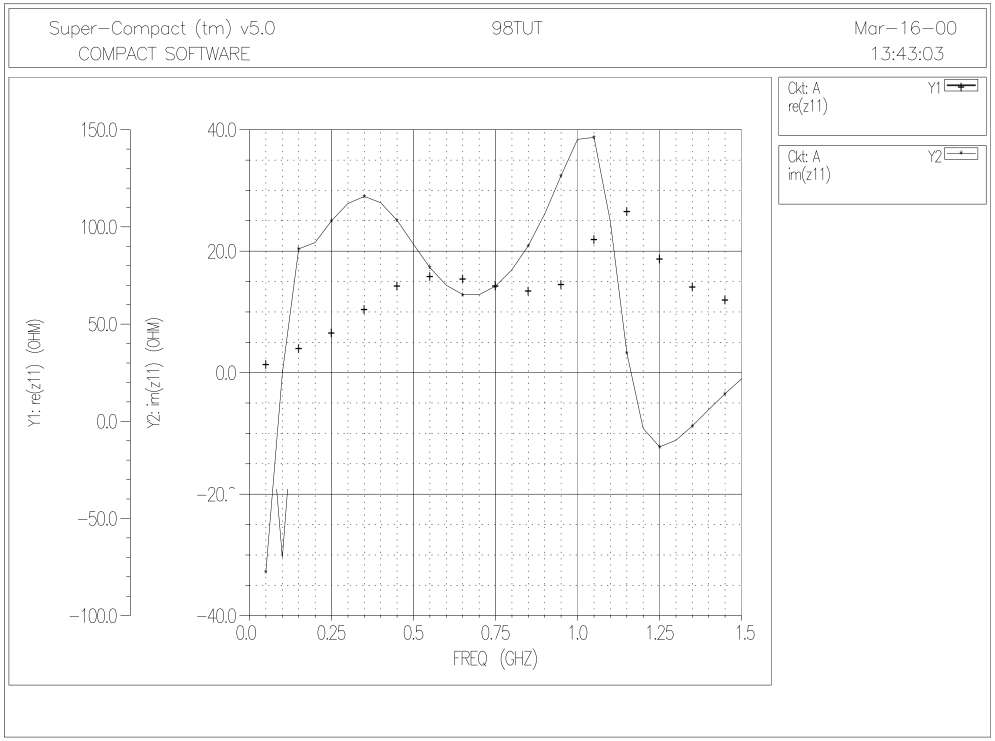
100MHz Oscillator Sustaining Stage Circuit Simulation: 50MHz to 1.5GHz



- 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

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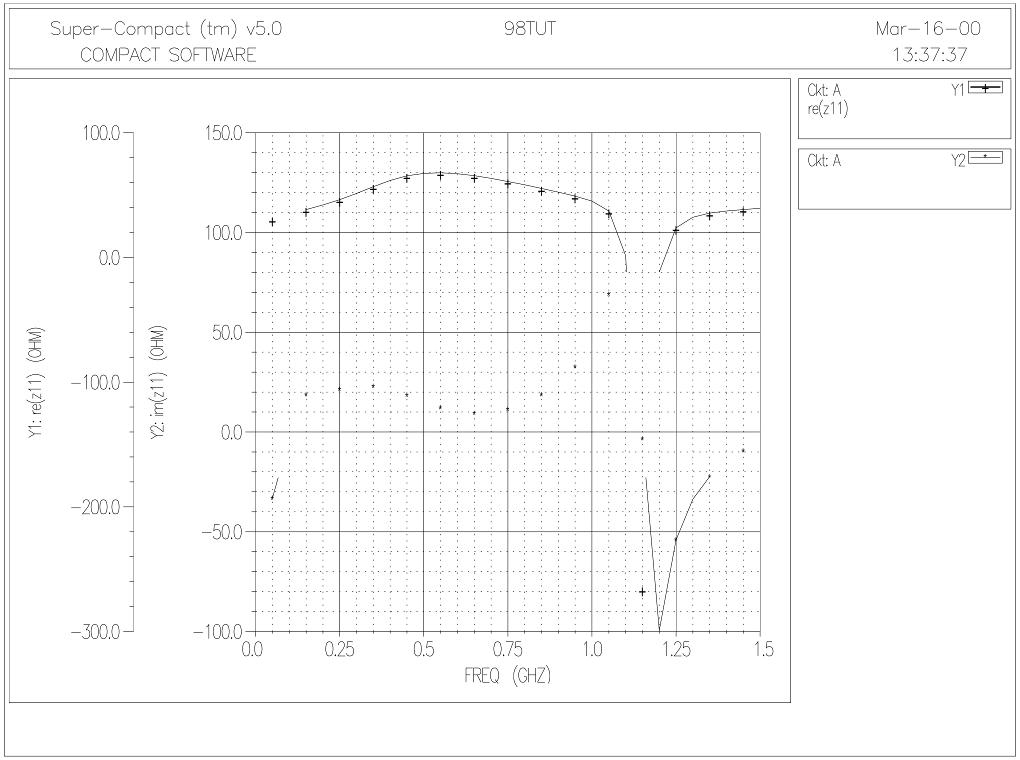
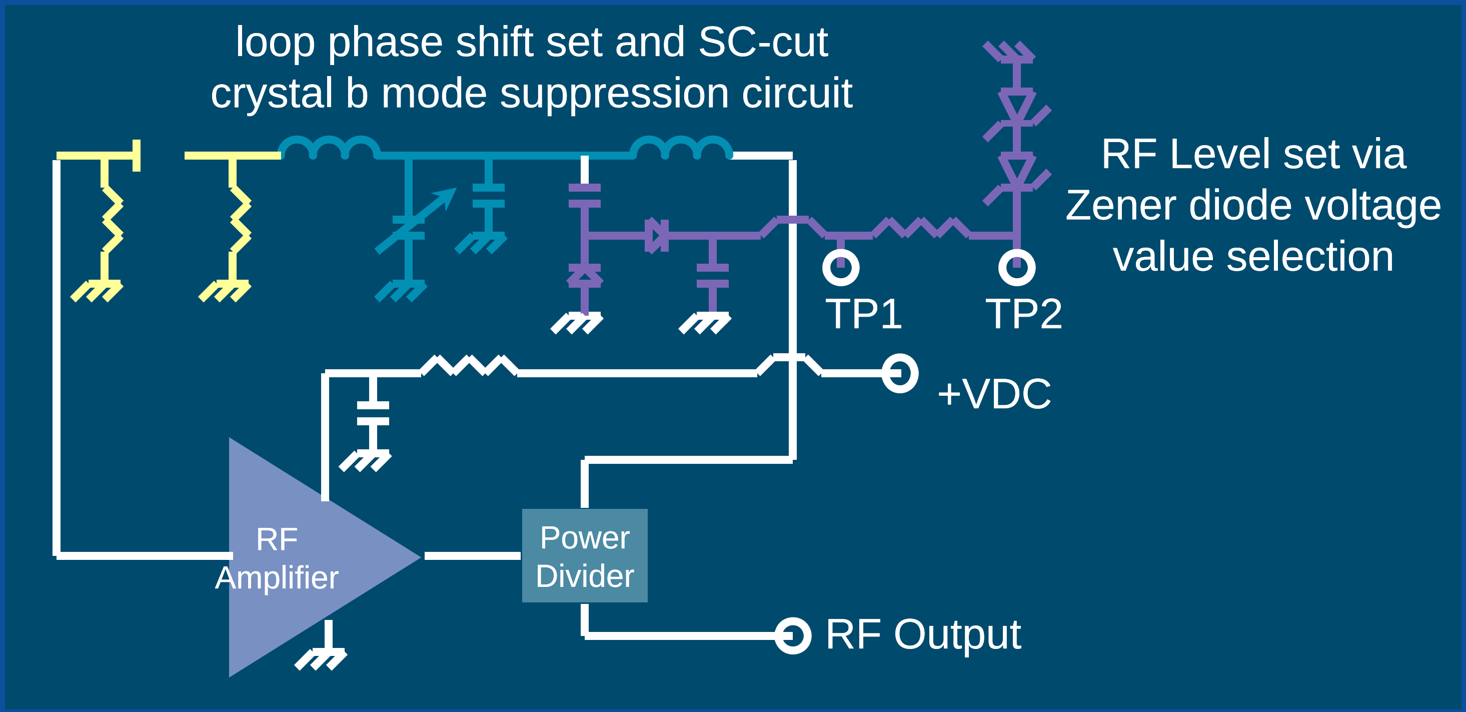
Results of 100MHz Oscillator Sustaining Stage Circuit Simulation



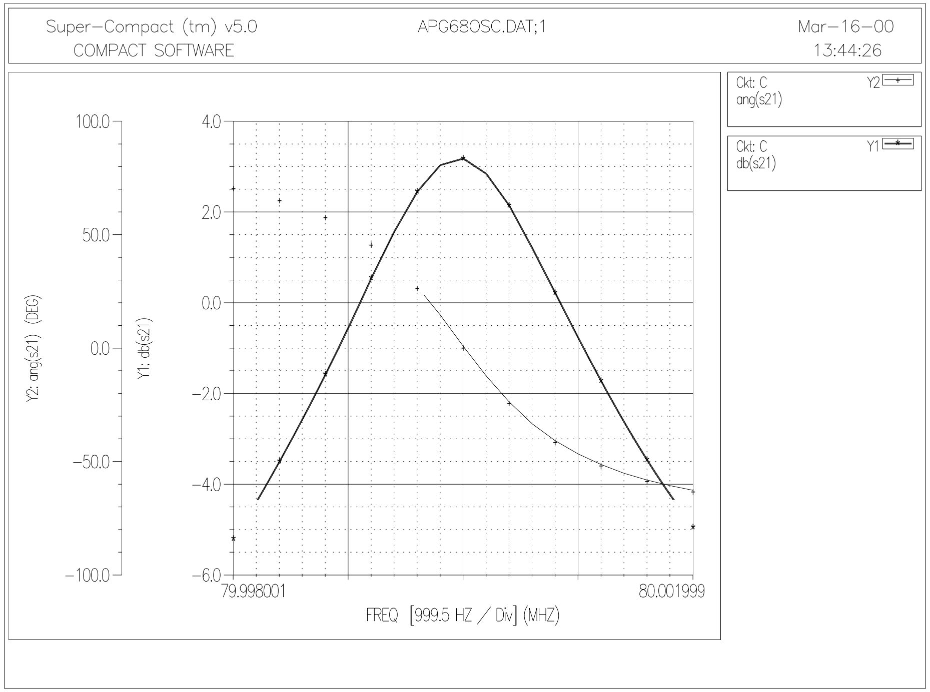
- 50MHz to 1.5GHz; collector resistor (Rc) *removed*
- Note that the real part of the impedance becomes highly negative1.15GHz
- This fact points to a probable circuit oscillation at/near 1.1GHz

80MHz Crystal Oscillator Using Modular Amplifier Sustaining Stage and Diode ALC



- 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.

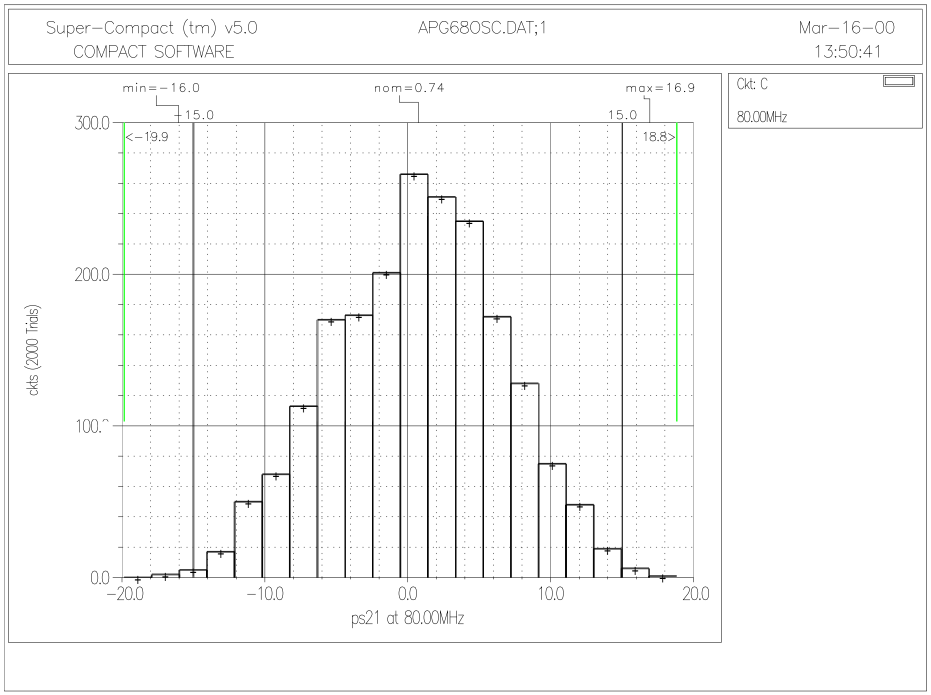
80MHz Modular Amplifier Oscillator Circuit Simulation



- 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)

- 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 $S\phi(f)/2$ noise power spectral density function of the form:

$$10^{K1/10}/f+10^{K2/10}$$

K1 = 1Hz 1/f PM noise level, in dBc/Hz

K2 = white PM noise "floor" level, in dBc/Hz

Reference: Mourey, Galliou, and Besson, " A Phase Noise Model to Improve the Frequency Stability of Ultra Stable Oscillator", Proc. 1997 IEEE Freq. Contr. Symp.

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.

Simple Oscillator Noise Modeling (cont.)

3. Calculate the oscillator <u>closed</u> loop signal PM noise sideband level as (for example):

$$\mathcal{L}(f) = 10LOG[(((S\phi_1(f)/2)+(S\phi_2(f)/2))(H_a(f)))+(S\phi_2(f)/2))(H_b(f))+ S_{\phi 3}(f)/2...)((1/2\pi\tau)^2+1)]$$

- H(f) terms are the normalized transmission responses of frequency selective circuitry as a function of carrier offset (modulation) frequency, and τ 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 **$((1/2\pi\tau)^2+1)$** term accounts for the conversion of open loop phase fluctuations to closed loop frequency fluctuations in the oscillator.

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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).

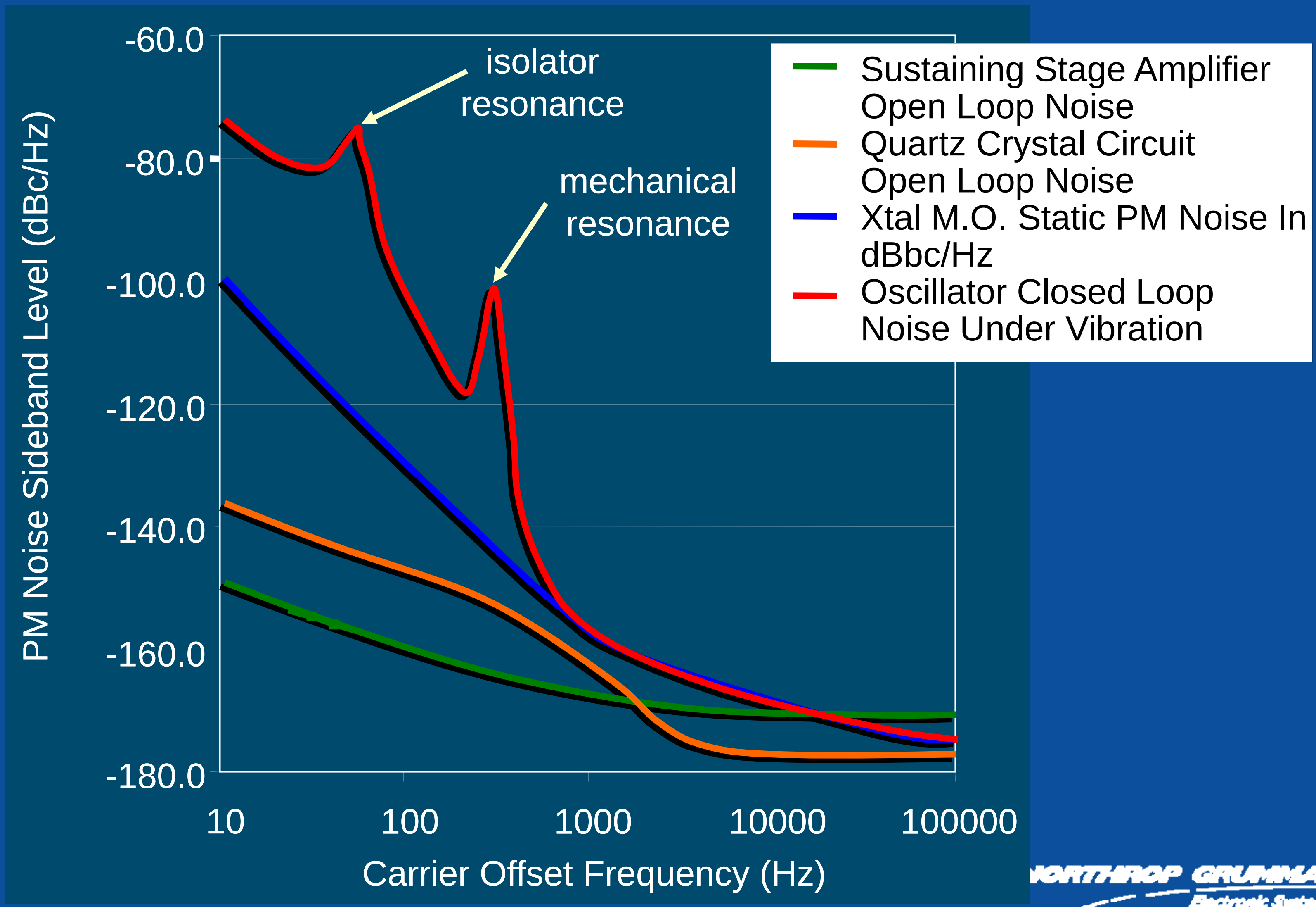
- The advantage of modeling the frequency-determining element instability as an open loop, phase fluctuation spectrum is that the spectrum used can be data collected from separate, phase bridge measurements of the phase instability induced onto a carrier signal by the device with corrections made for any differences in in-bridge vs in-oscillator circuit loading

Oscillator Noise Modeling - Vibration

- 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

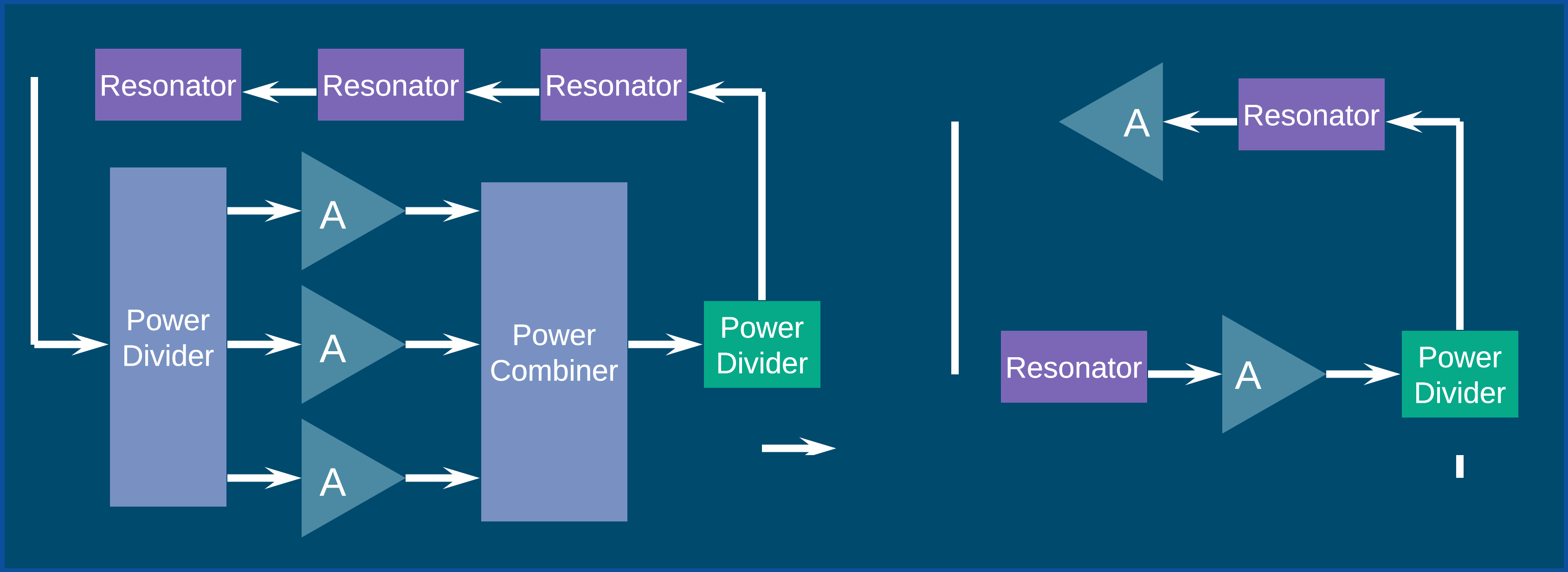


8. Oscillator Noise De-correlation/Noise Reduction Techniques

Methods to Reduce Noise Internal to the Oscillator Circuit

- Use the resonator impedance and/or transmission selectivity to “filter” the noise at carrier offset frequencies beyond the resonator half-bandwidth.
- Use parallel sustaining stage amplifiers (amplifier 1/f PM noise de-correlation).
- Use multiple, series connected resonators (resonator 1/f FM noise de-correlation).
- Use multiple resonators in an isolated cascade or multi-pole filter configuration (increased loop group delay).

Example: Multiple Device Use for Noise Reduction

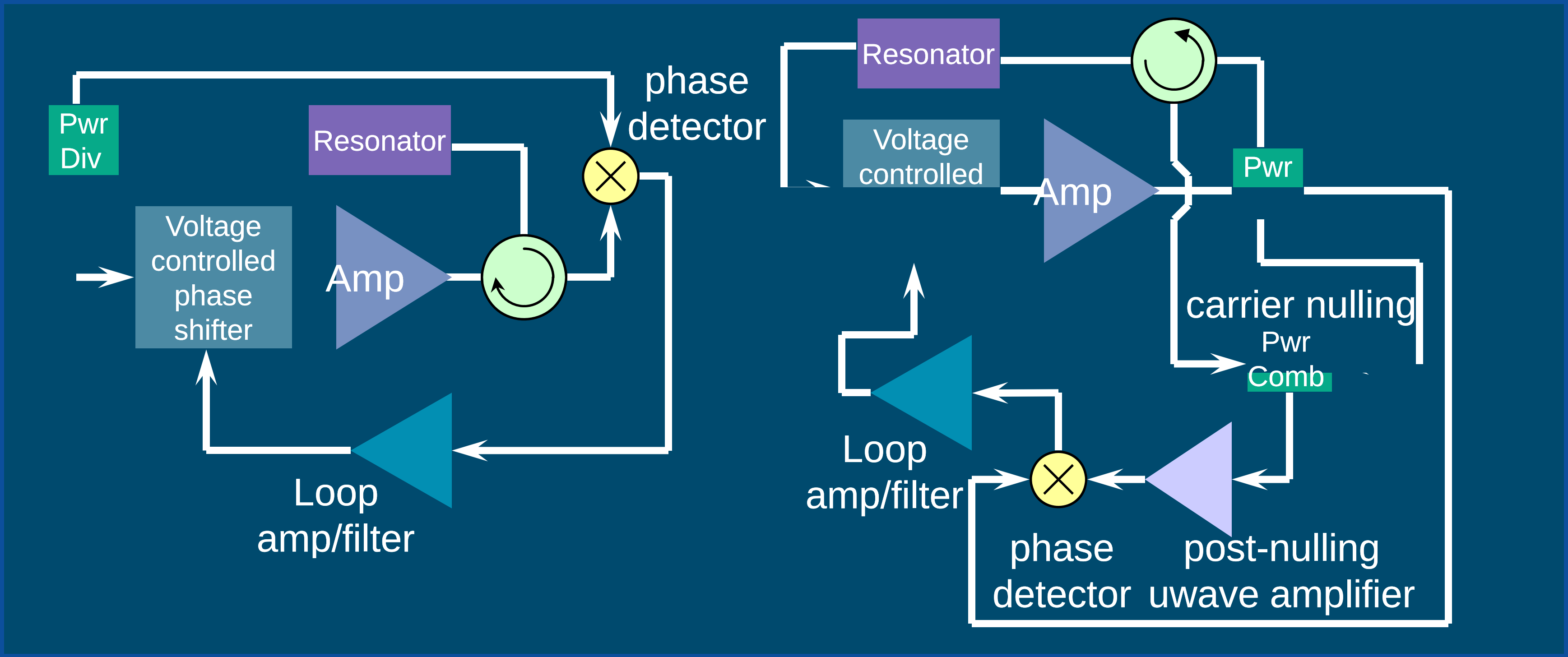


- Noise de-correlation in amplifiers and/or resonators
- Cascaded amplifier-resonators to increase loop group delay

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)
  - feed-forward noise cancellation

Examples:
Noise Reduction Techniques

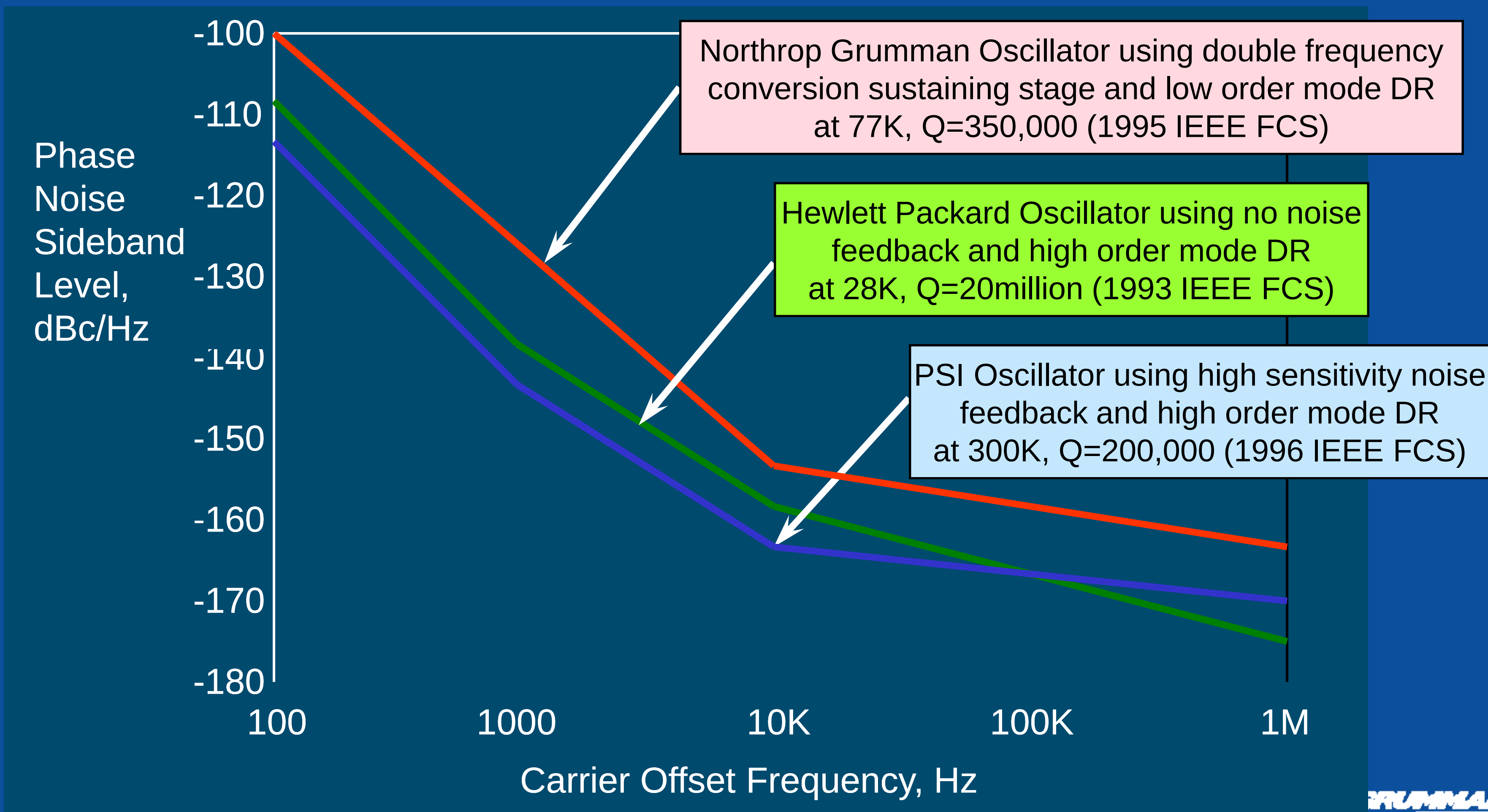


Use of resonator response to increase phase detector sensitivity (JPL and Raytheon)

Carrier nulling with post-nulling uwave amplifier used to increase phase detector sensitivity (Univ. Western Australia and Poseidon Scientific Instruments)

Advantages of Noise Feedback in X-Band, Sapphire Dielectric Resonator (DR) Oscillators

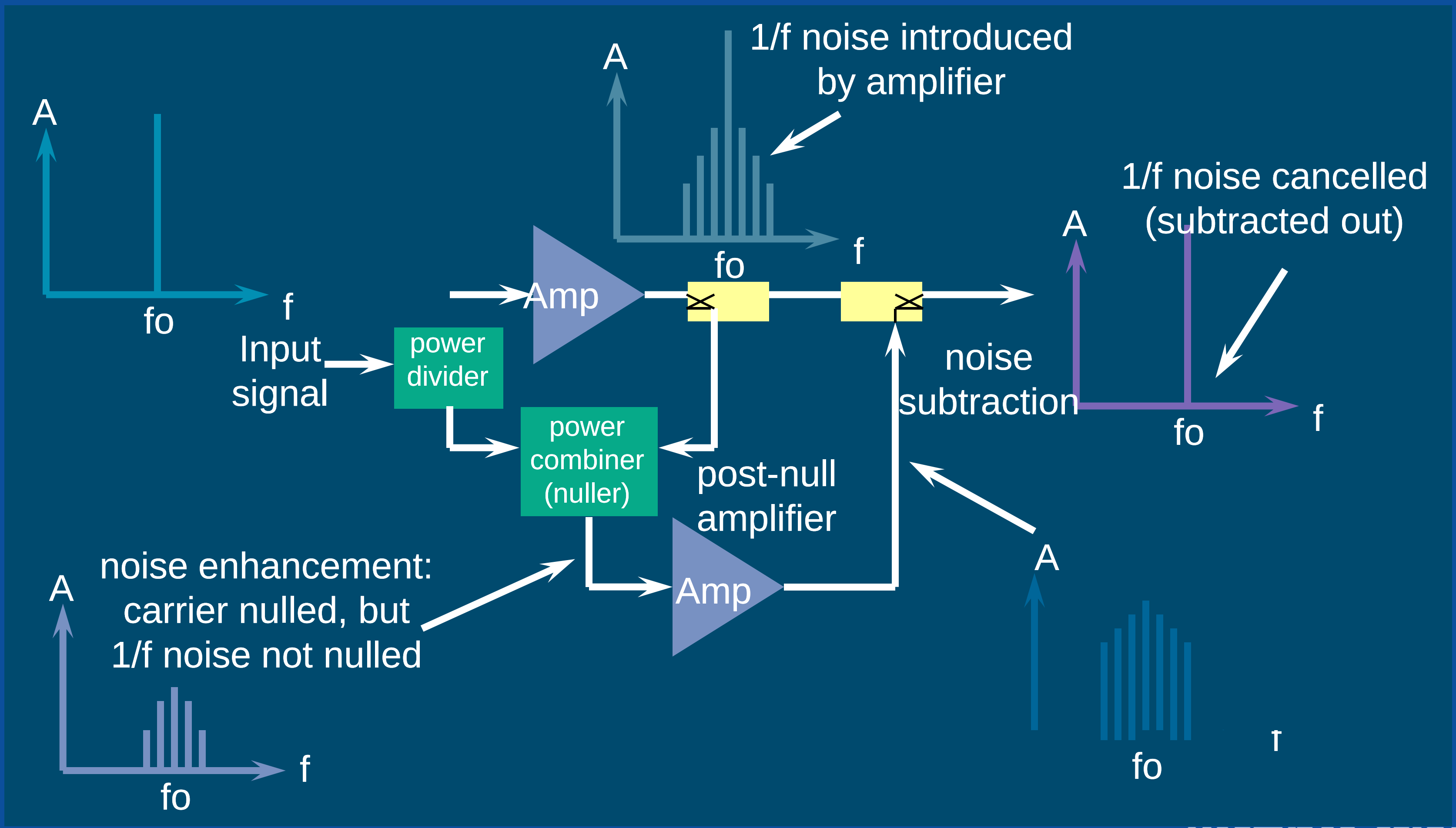
- Lower Noise with 60 times lower Q



*Amplifier Noise Reduction via Feed-forward Cancellation**

(no noise down-conversion to base-band)

*amplifier operated linearly



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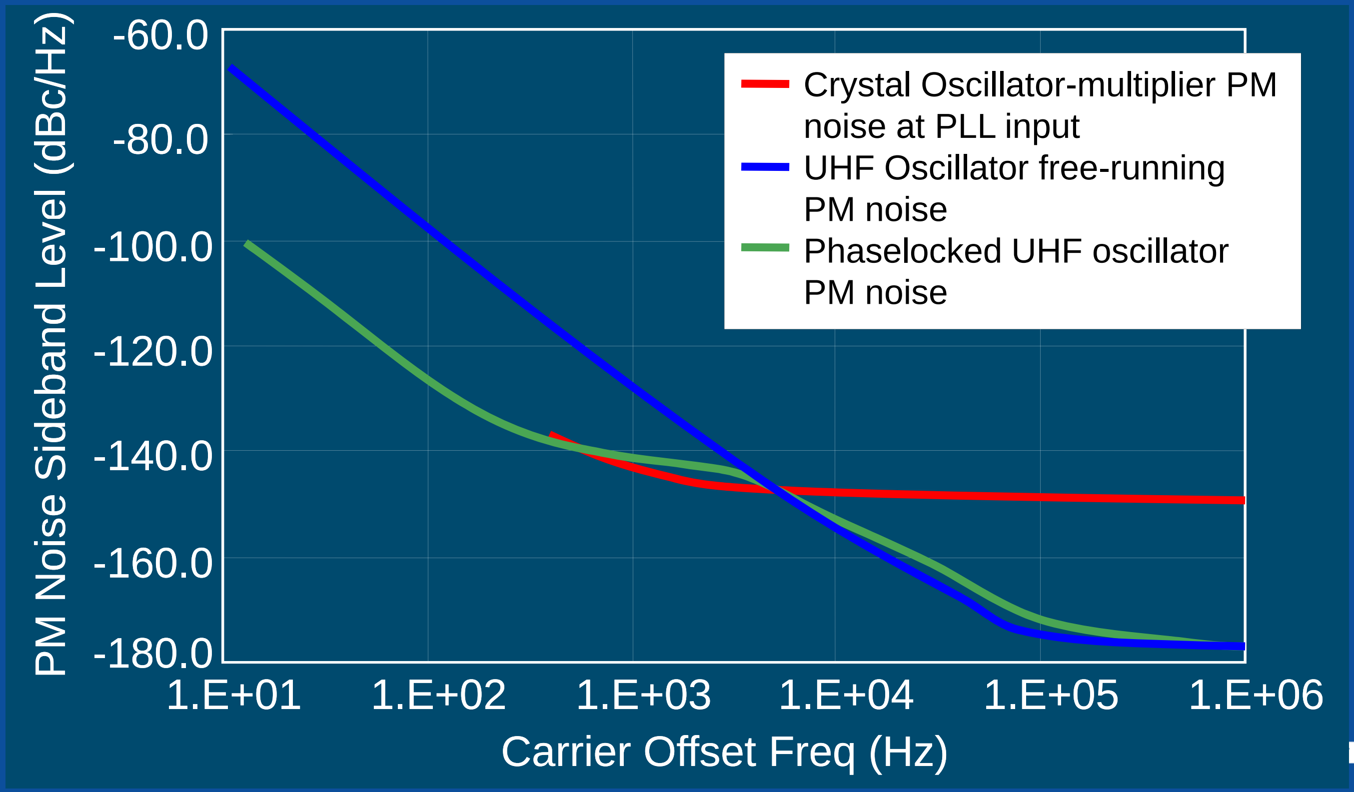
Methods to Reduce Noise External to the Oscillator Circuit

- External active (phase-locked VCO) or passive, narrow-band spectral cleanup filters
- Overall subsystem noise reduction via feedback or feed-forward noise reduction techniques

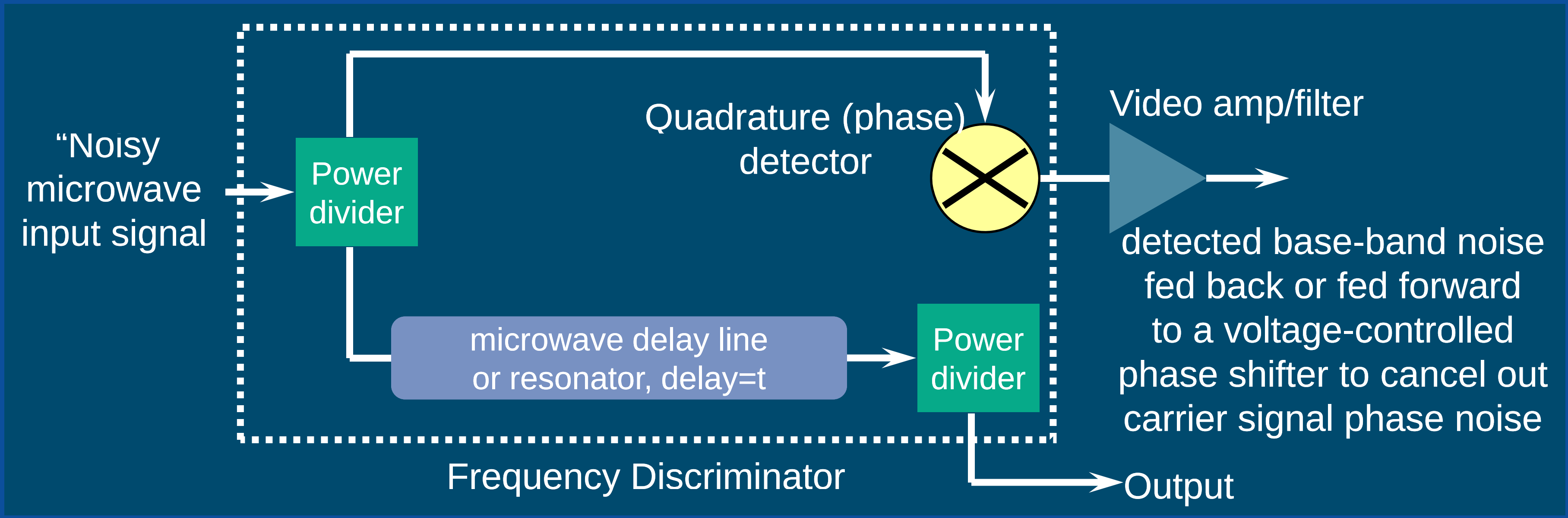
UHF VCO Phaselocked To HF Crystal Oscillator:

- 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)



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



9. Summary

Designing the Optimal Oscillator

- Identify the oscillator/resonator technology best suited for the application (to meet the specification).
  - 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 and carrier phase sensitivity to DC supply variation at the operating drive level.
- Know or measure the resonator and non-resonator circuit vibration sensitivities and package mechanical resonance characteristics.
- Qual test the final prototype oscillator to verify performance.

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
  - Simplified circuit noise reduction schemes (feedback, etc, using low cost ICs)
- Improved vibration sensitivity reduction schemes
  - Cancellation, feedback control, mechanical isolation, etc.

Finally Finished!!

(Thanks for your patience)

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