Low Noise Oscillator Design and Performance

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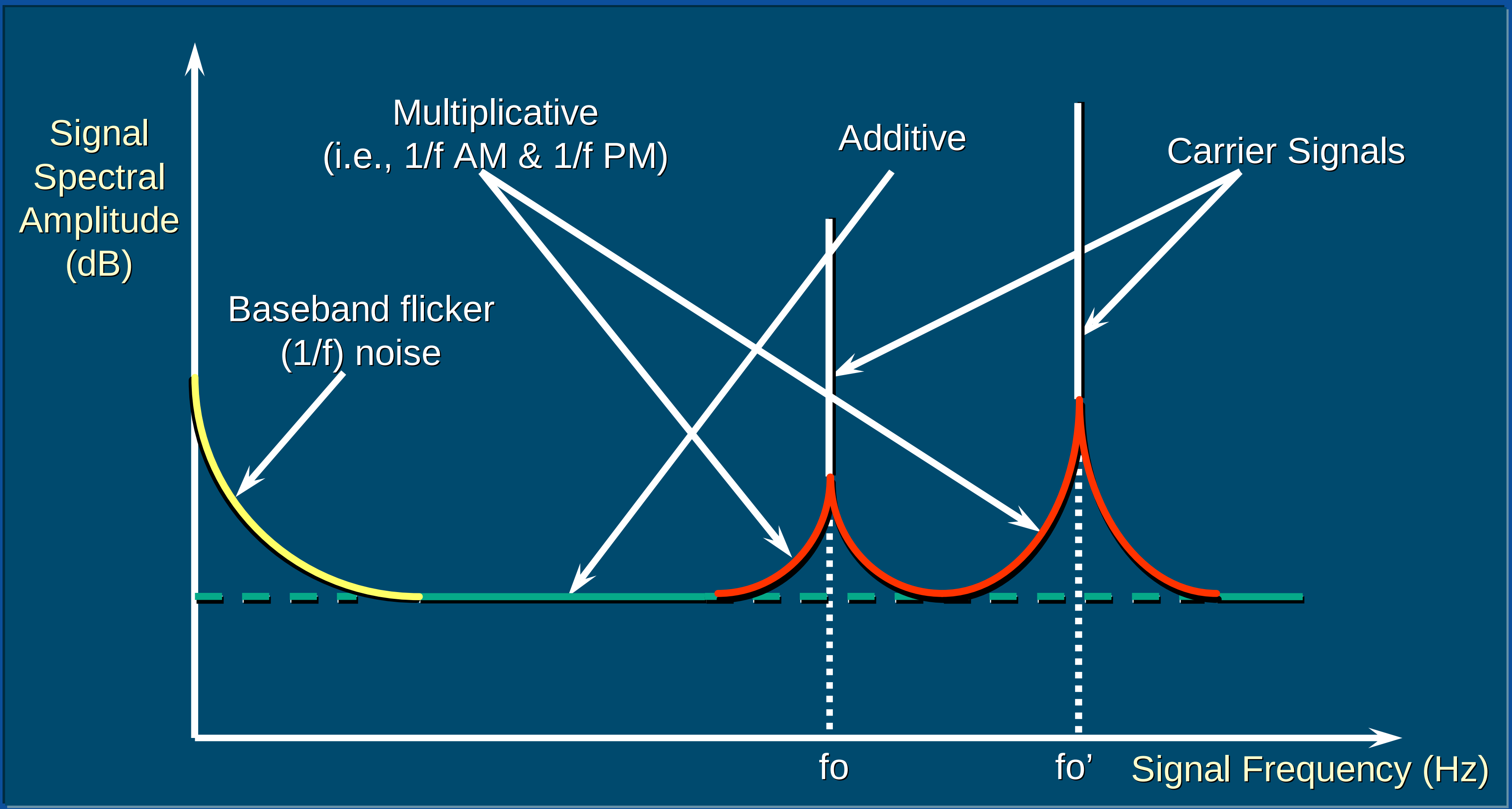
Types of Phase and Amplitude Noise



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Types of Phase and Amplitude Noise (cont.)

Additive Noise [noise power <u>independent</u> of signal]

Thermal noise:	$en^2=4KTRB$	K = Boltzman's constant = $1.374X10^{-22}$ T = temp in Kelvin = 300K at room temp. R = resistance in ohms B = bandwidth

Shot noise:	$in^2=2qIB$	$q=1.59X10^{-19}$ I=current in amperes

How to Calculate Additive Noise

Amplifier additive noise power

KTBF (Rg=50 ohms, T=300K, B=1Hz), referred to input = -174dBm/Hz + NF(dB)

Carrier Signal-to-Noise Ratio

in dBc/Hz = -174 + NF(dB) - input signal power (dBm)

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

in dBc/Hz = -177 + NF(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 (gm) 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

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

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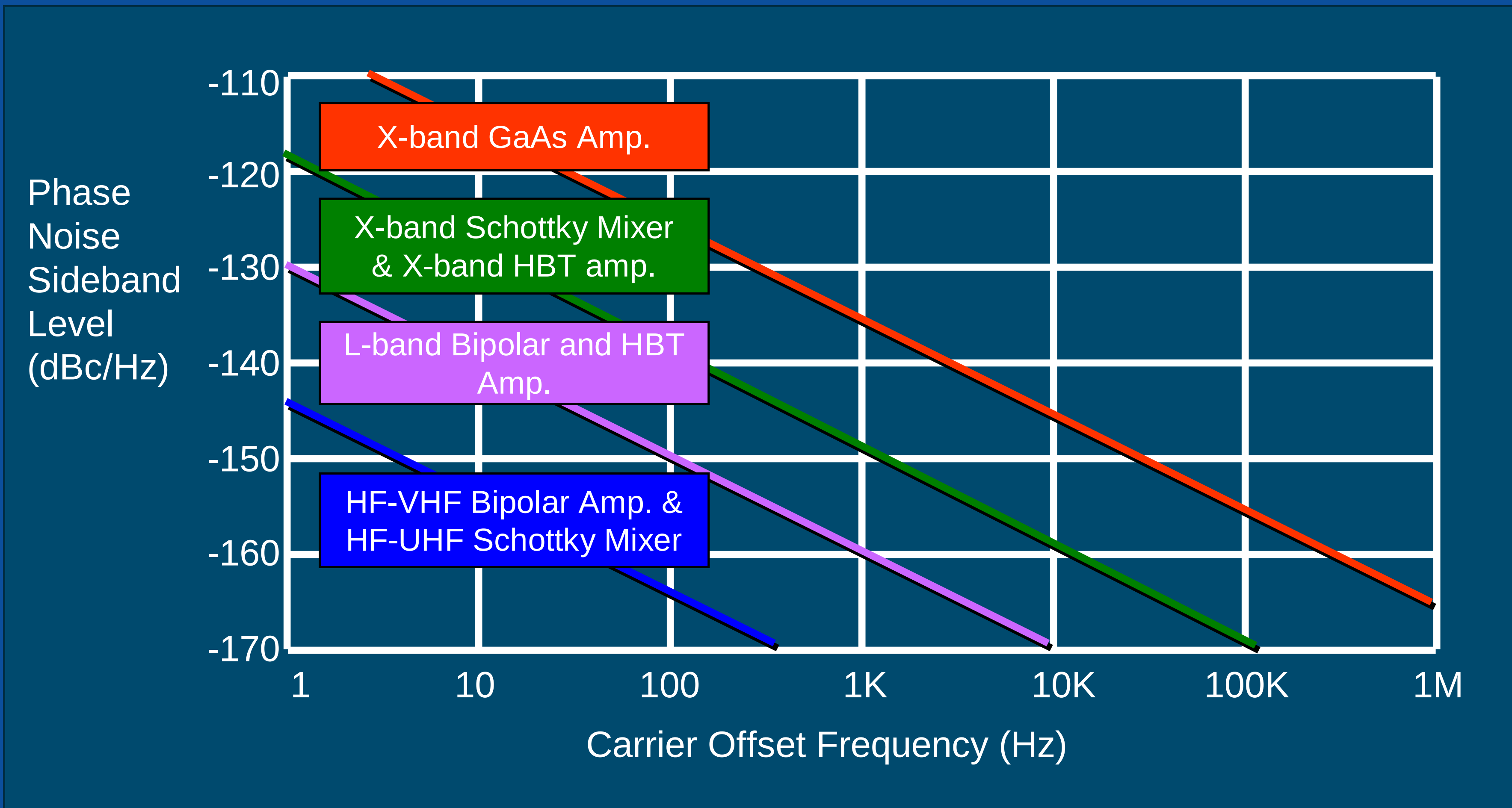
Characteristics of Multiplicative Noise (continued)

- 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

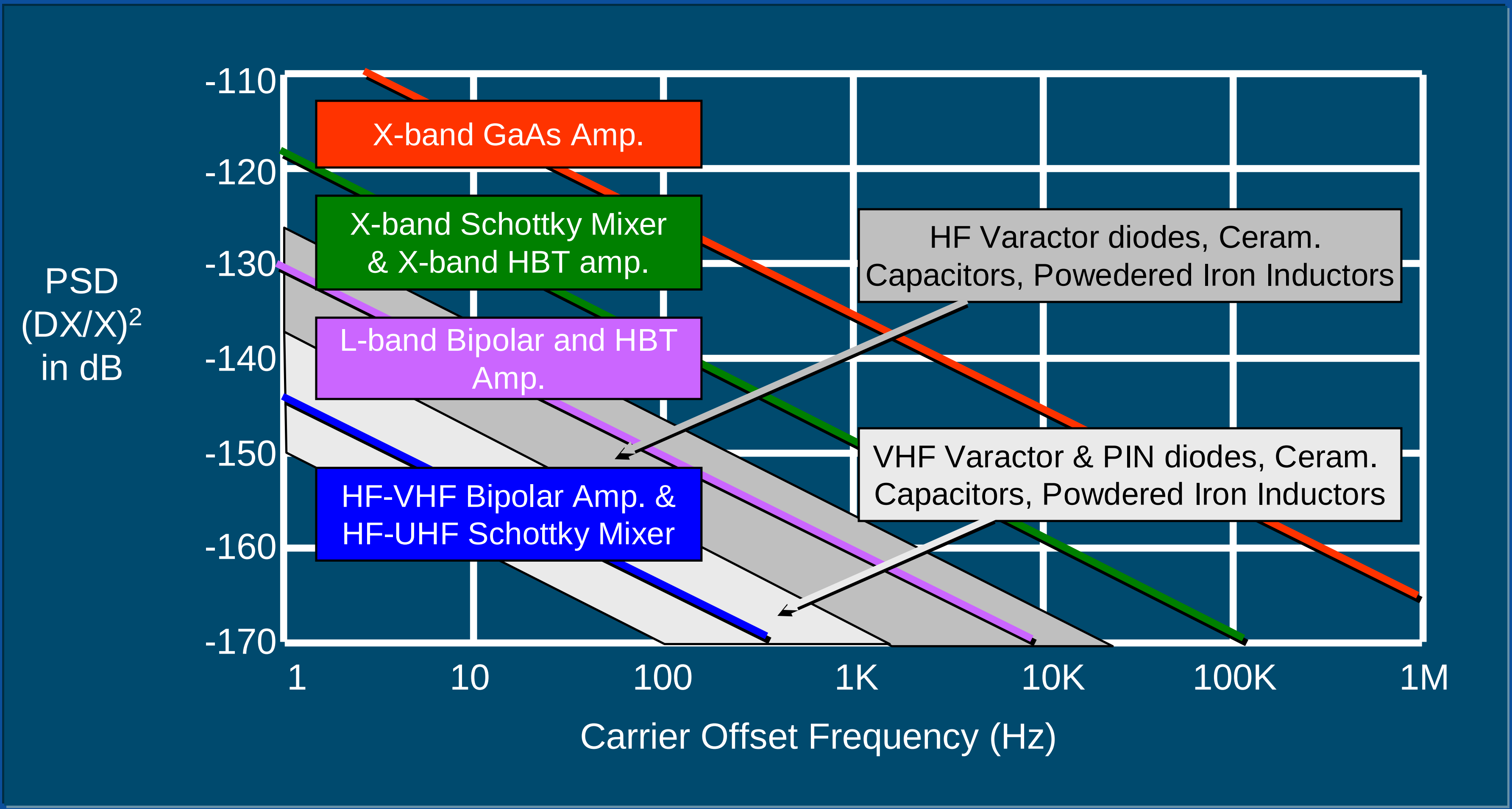
"Typical" Component 1/f PM Multiplicative Noise Levels



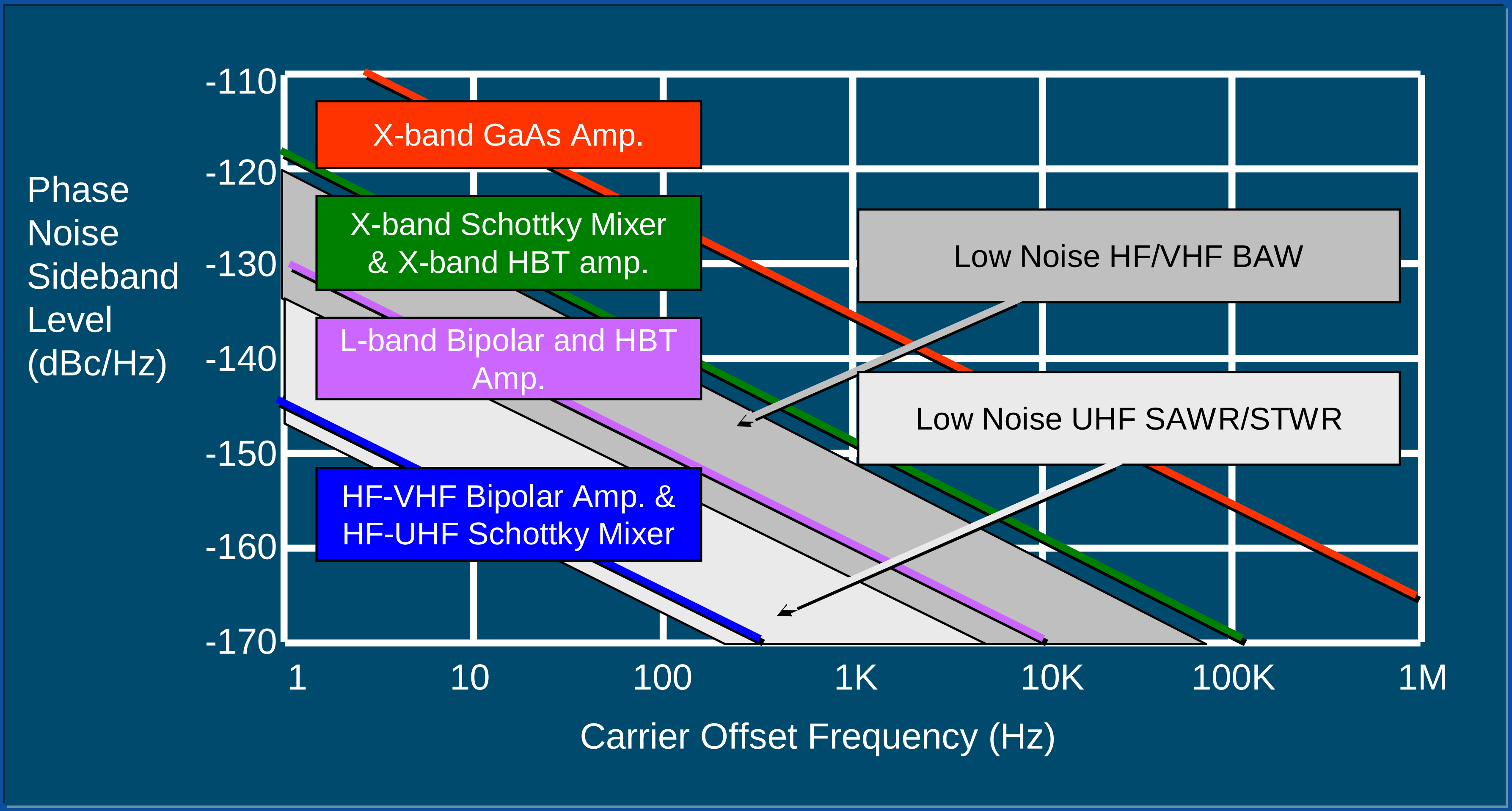
Component 1/f Instability

- 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)

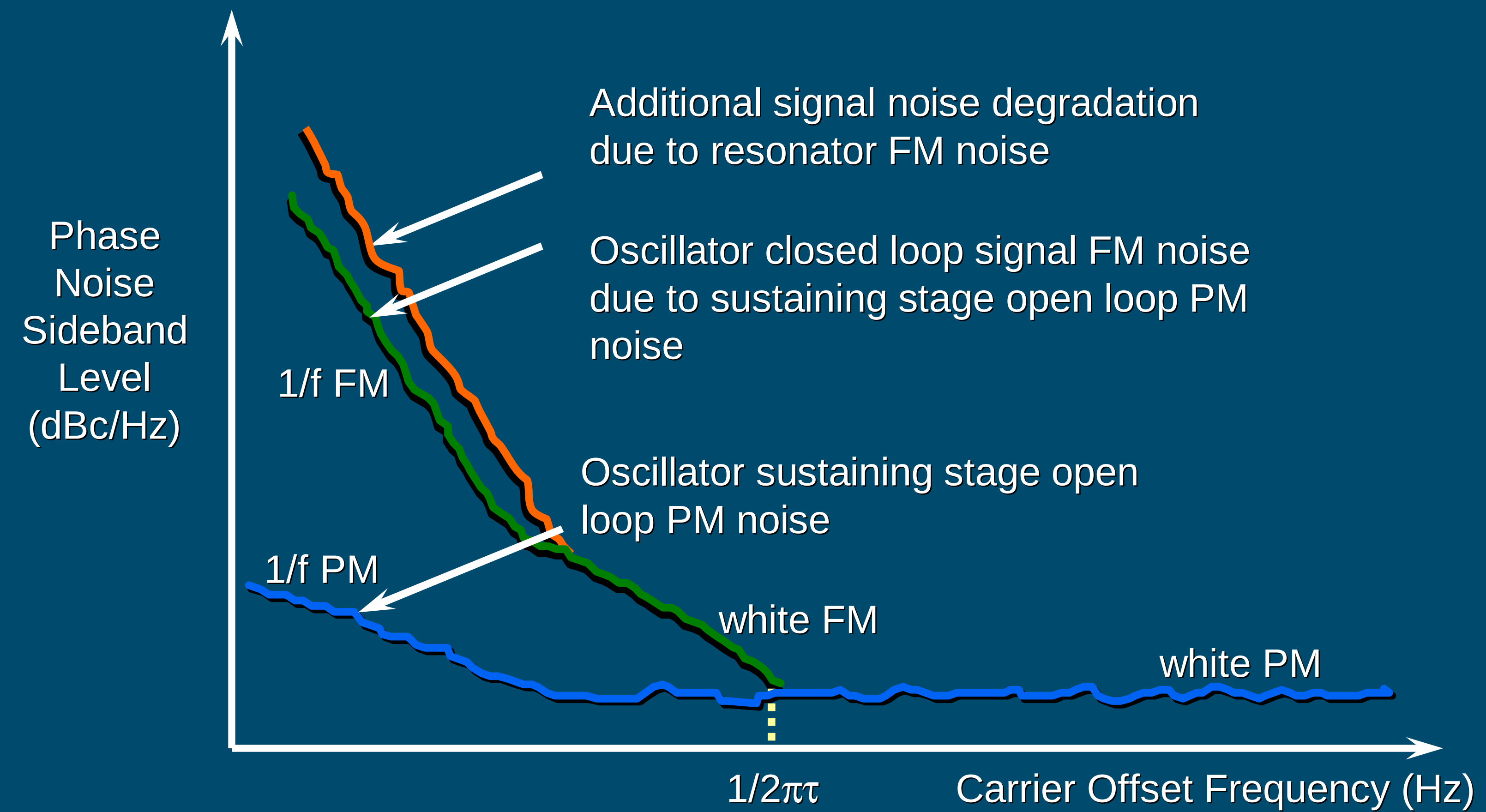
Passive Component 1/f Impedance Instability



Resonator Open Loop Phase Instability



PM-to-FM Noise Conversion in an Oscillator



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

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:

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

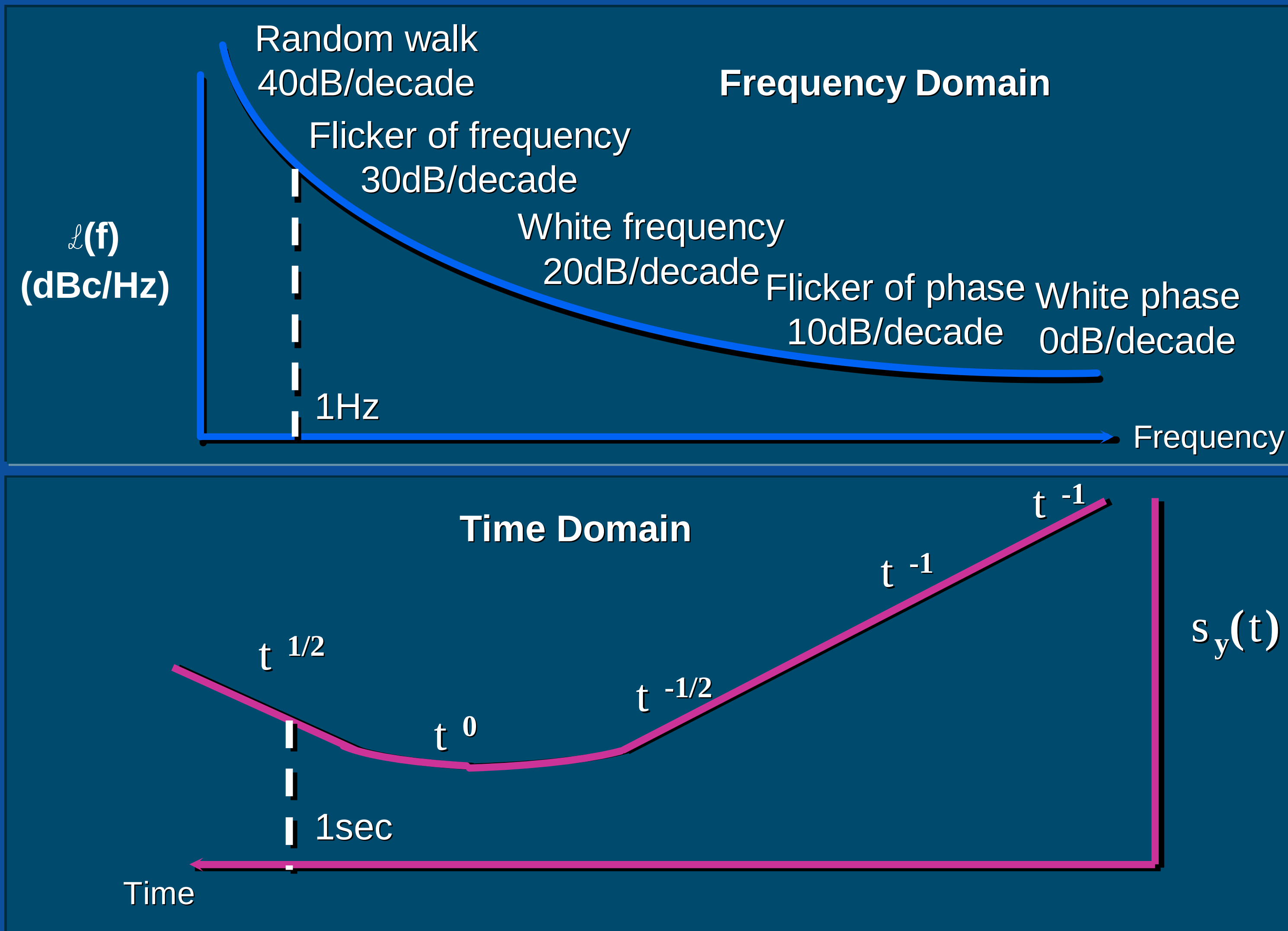
$S_\phi(f)$ = Spectral density of the phase fluctuations (rad^2/Hz).

$S_y(f)$ = 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



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

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

ν_0 = carrier frequency

f = fourier frequency

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

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

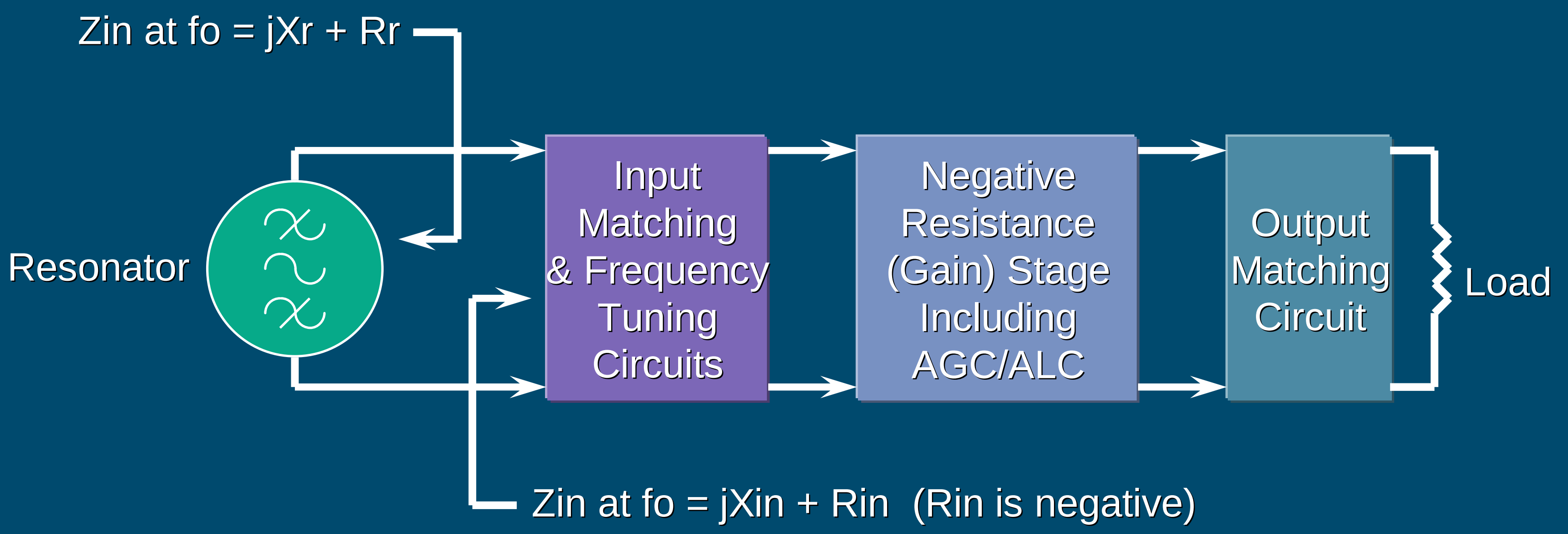
$\sigma_y^2(\tau)$ in the region

$\tau = 1/f = 1sec = (2)(\ln(2))(Sy(f))(f) = 2.77X10\text{-}22$

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

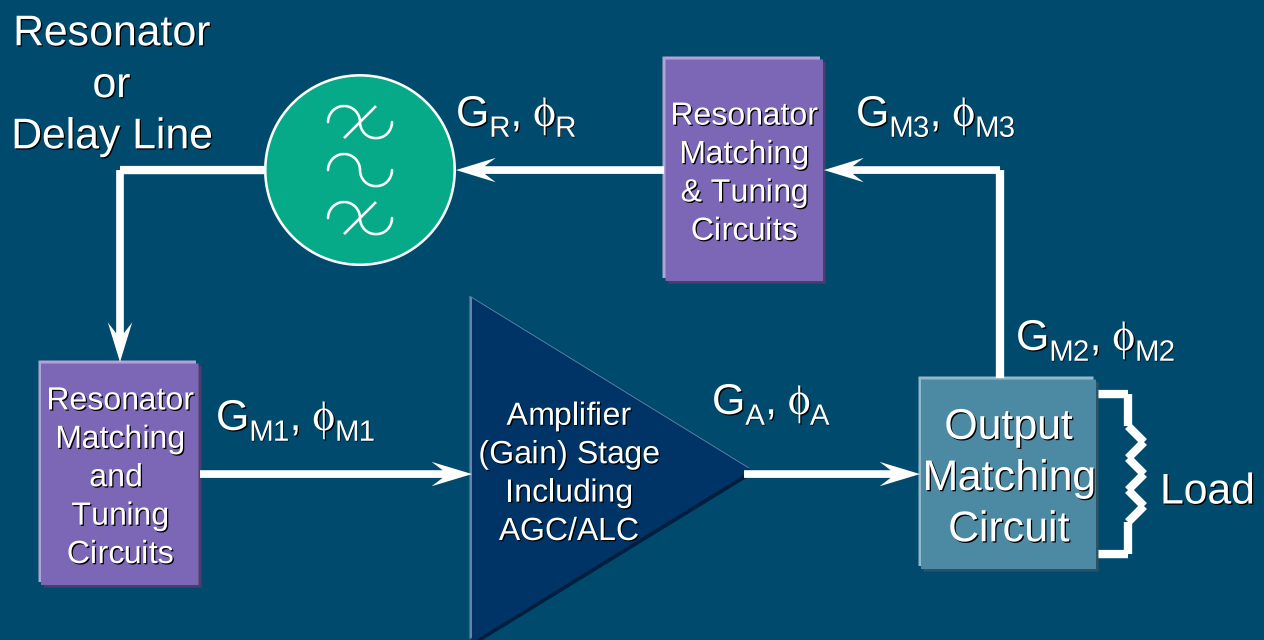
2. Basic Oscillator Operation

Oscillator Viewed as a Two Terminal Negative Resistance Generator



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

Oscillator Viewed as a Feedforward Amplifier with Positive Feedback



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

Steady State: $G_{M1}G_AG_{M2}G_{M3}G_R= 1$, $\phi_{M1}+\phi_A+\phi_{M2}+\phi_{M3}+\phi_R = 2N\pi$ radians

ALC / AGC Must Occur

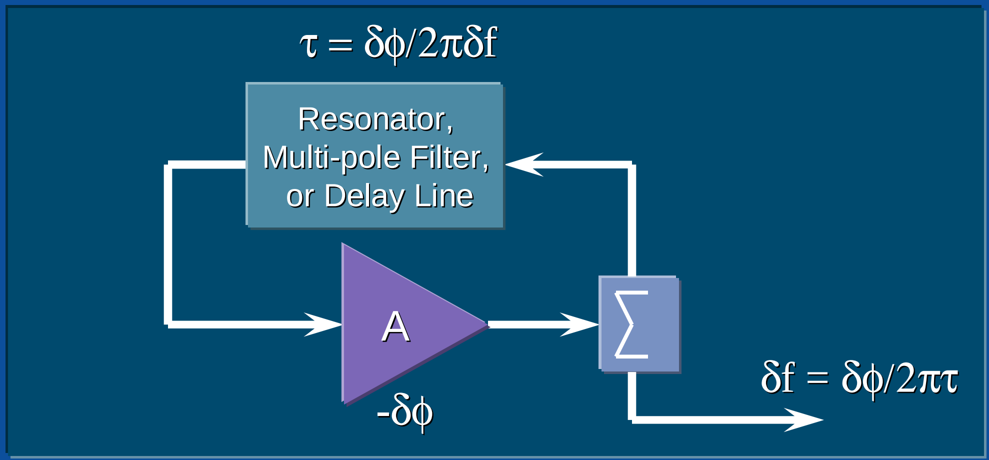
- Types of automatic level control (ALC) and/or automatic gain control (AGC):
  - (1) Instantaneous signal amplitude limiting/waveform clipping via sustaining stage amplifier gain compression or separate diode waveform clipping.*
  - (2) Gain reduction using a feedback control loop. The oscillator RF 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

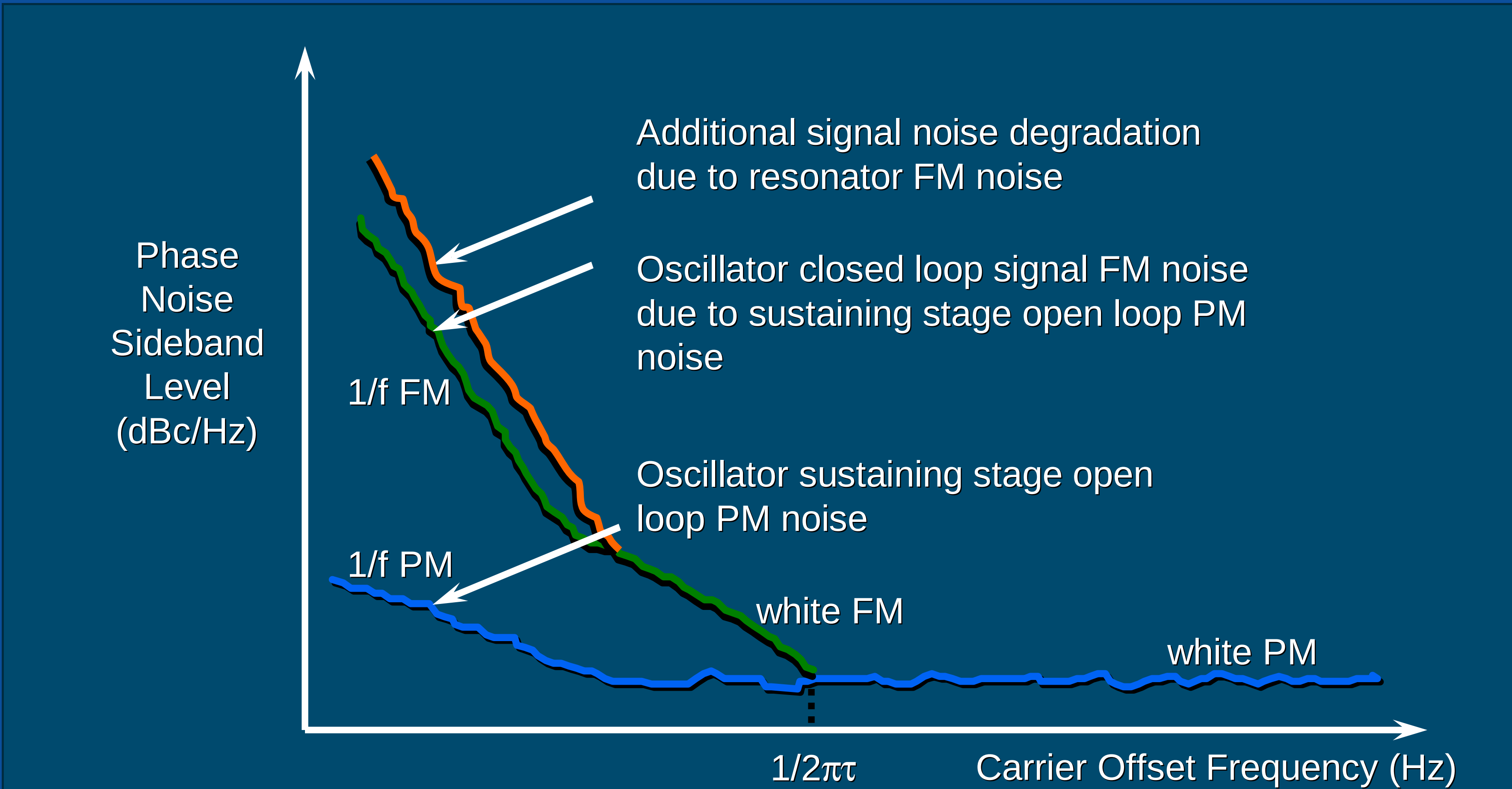


- If a phase perturbation, $\delta\phi$ occurs in an oscillator component (i.e., sustaining stage amplifier phase noise), the oscillator signal frequency must change in order to maintain constant ($2n\pi$ radians) loop phase shift
- The amount of signal frequency change caused by the phase perturbation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

Conversion of Open-Loop Noise to Closed-Loop Noise (cont.)

- The conversion process can be described by:
  - Closed-loop $S_\phi(f)$ = open-loop $S_\phi(f)(1/2\pi\tau f)^2$
  - Noise sideband level = $\mathcal{L}(f) = 10LOG(S_\phi(f)/2)$

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)
- 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

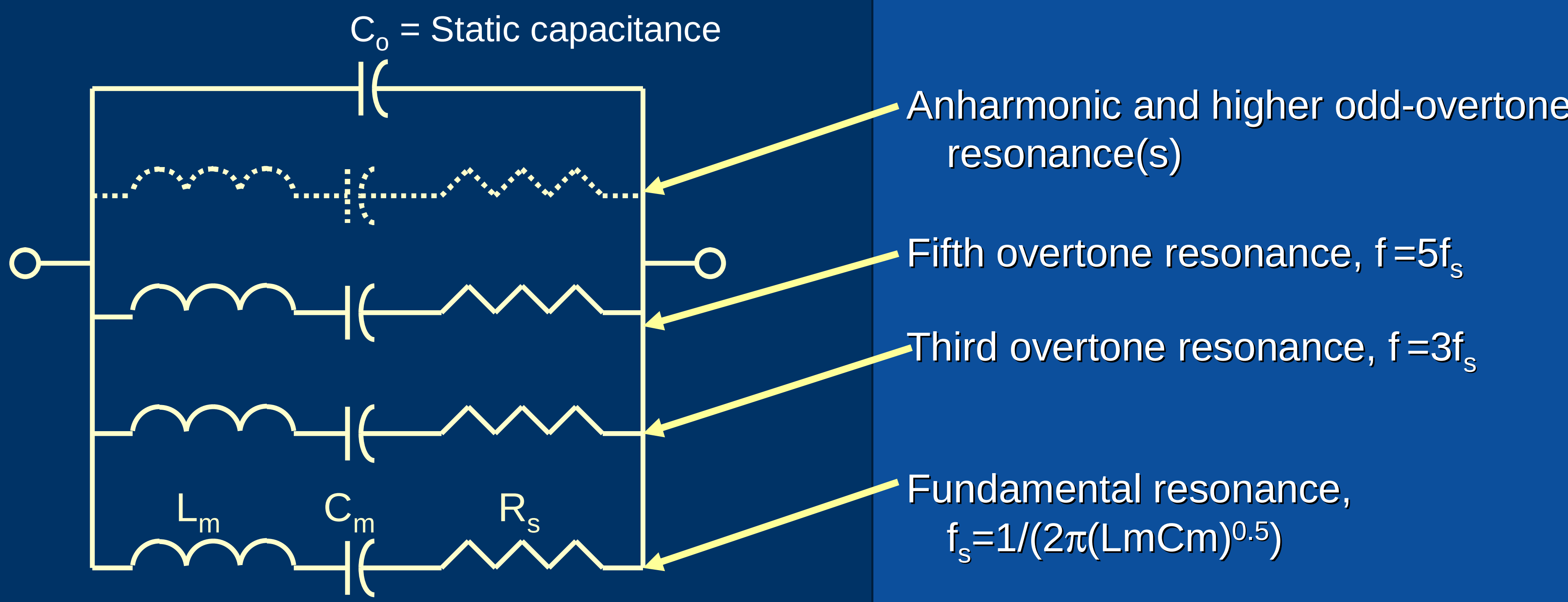
- Very high Q
- Controllable (selectable) frequency temperature coefficient
- Excellent long-term and short-term frequency stability
- Relatively low cost
- Moderately small volume (especially SAW, STW)
- Well defined, mature technology

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 Acoustic Resonators, continued

Quartz Crystal Electrical Equivalent Circuit
(for widely used AT-cut and SC-cut crystals)

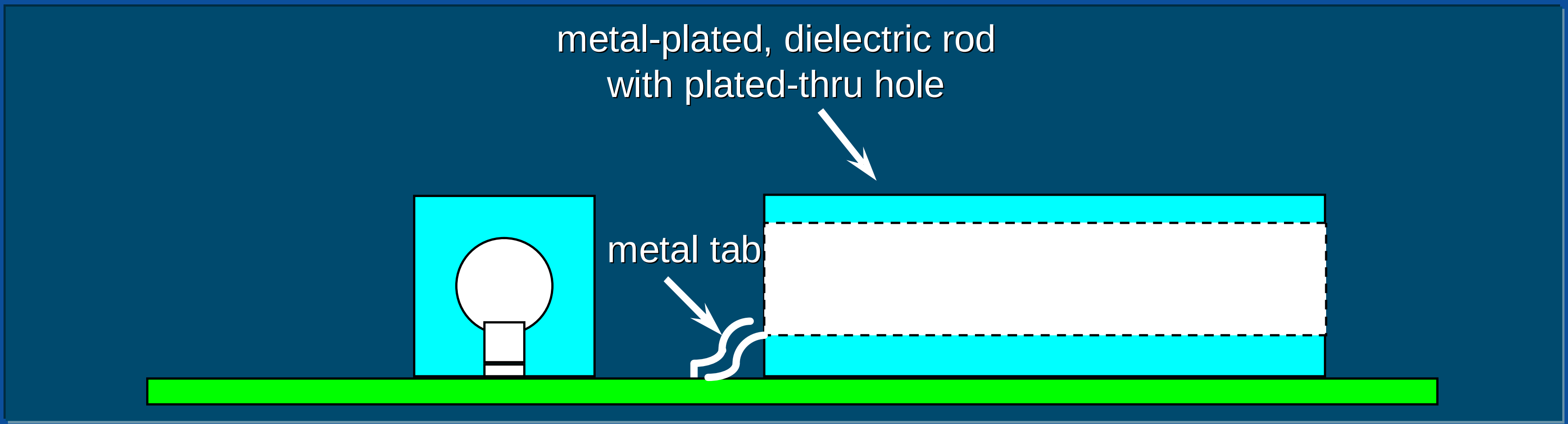


- L_m = motional (series) inductance
- C_m = motional capacitance
- R_s = series resistance $2\pi f_s/R_s$ = unloaded Q

Improvements in Acoustic Resonator Performance - 1985 to 1999

Year	Resonator Type	Frequency	Noise Level, Sy(f=100Hz) Nominal	Best	Pmax (mW)	Virbration Sensitivity (parts in 10^{-10}/g)
1985	5th OT AT-cut	80MHz	$1X10^{-24}$	$2X10^{-25}$	2	5 to 20
1985	Raytheon SAW	500MHz	$2X10^{-24}$	$4X10^{-25}$	50	5 to 50
1989	5th OT AT-cut	40MHz	$5X10^{-26}$	$1X10^{-26}$	2	10 to 30
1989	3rd OT S C-cut	80MHz 100MHz	$2X10^{-25}$	$4X10^{-26}$	7	3 to 10
1995	5th OT S C-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 S C-cut	100MHz	???	$\leq 1.6X10^{-26}$	???	???

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)
- 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 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

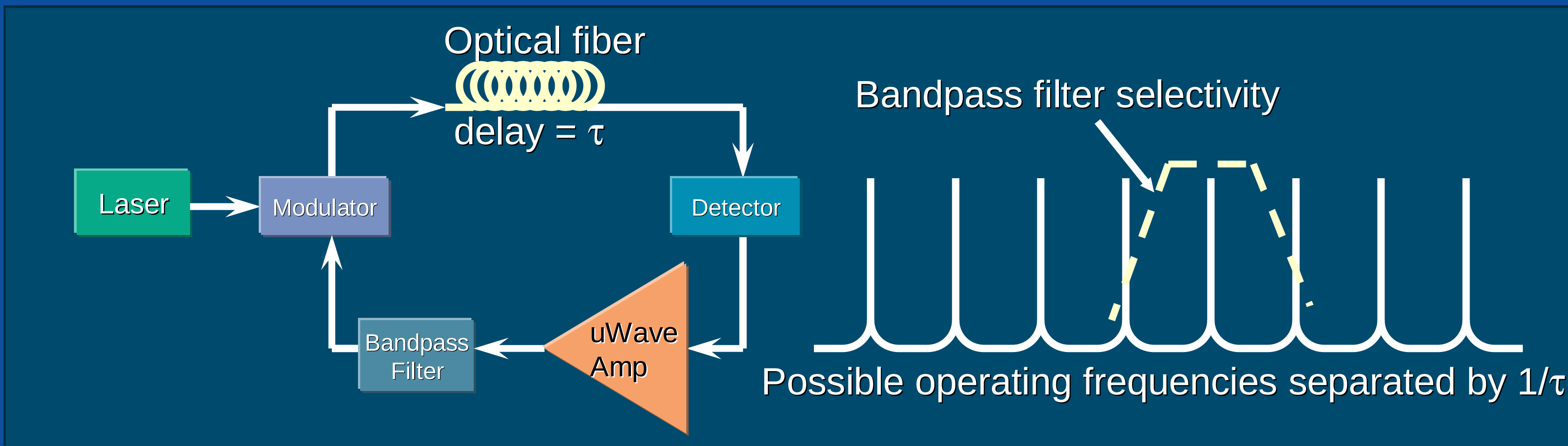
Advantages

- 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

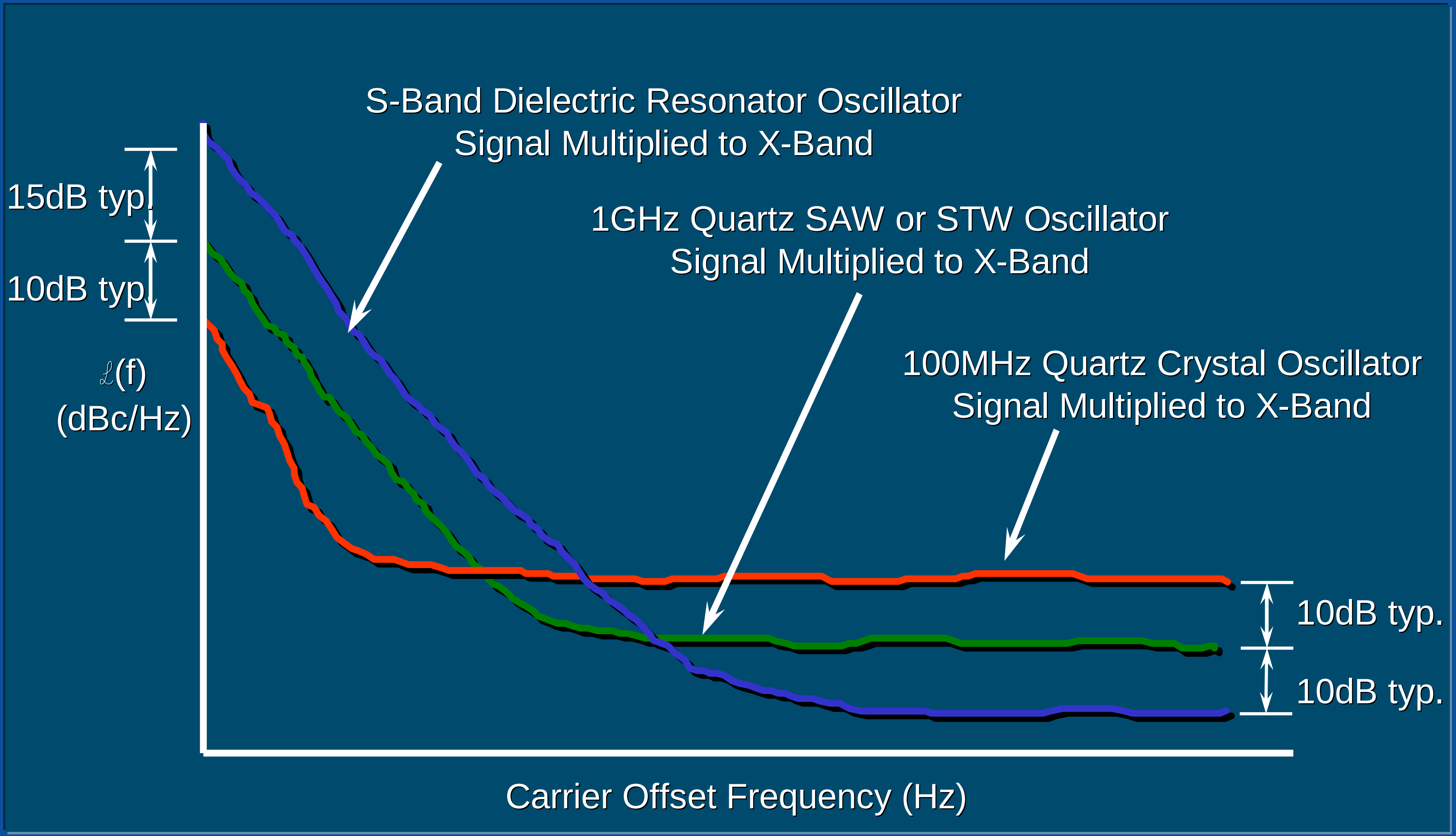
Opto-Electronic Oscillator (OEO)



- 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

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

Spectral Tradeoff: Near-Carrier vs Noise Floor Performance



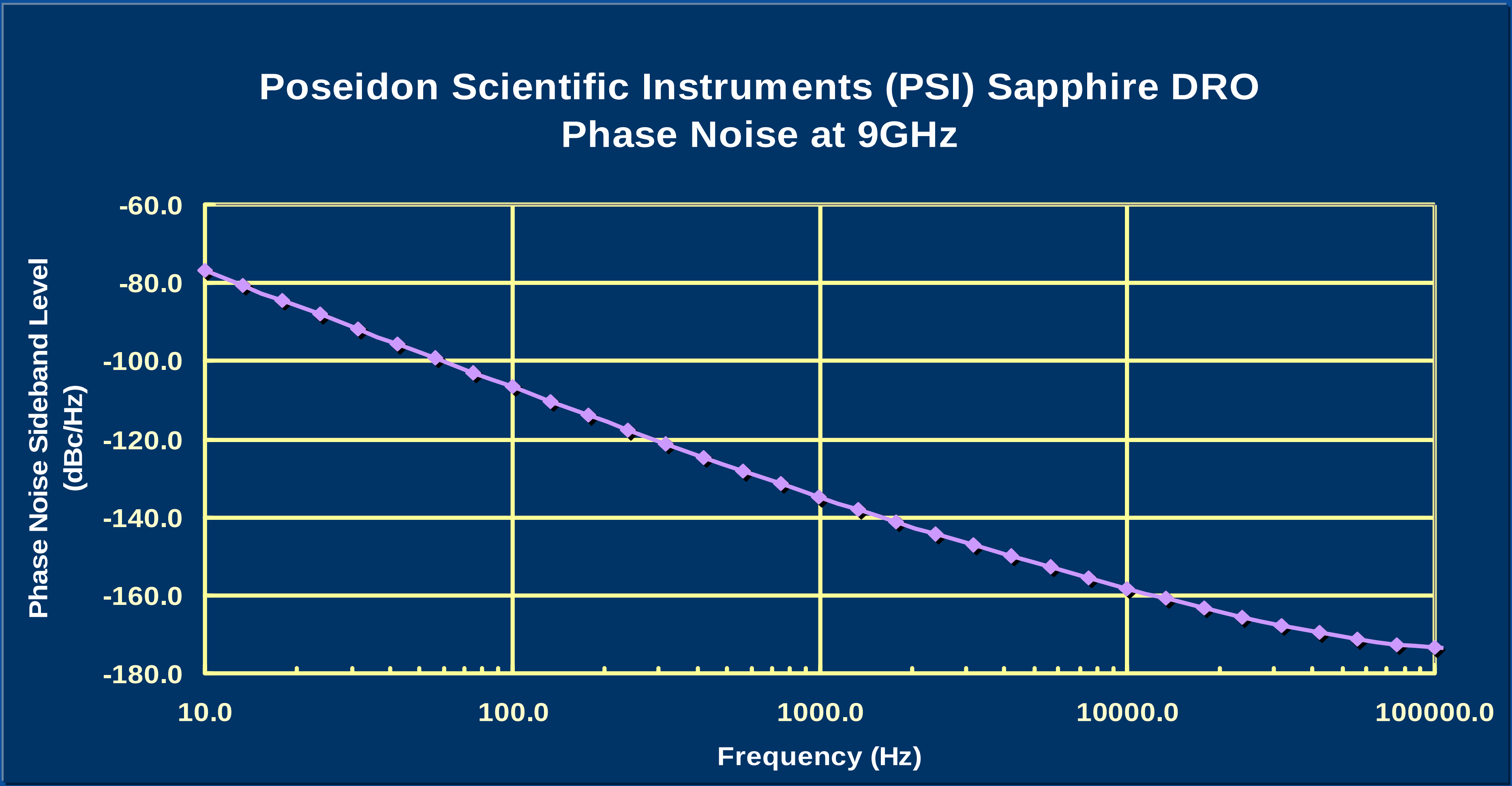
Whispering Gallery Mode, Sapphire Dielectric Resonators

- 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 10million 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



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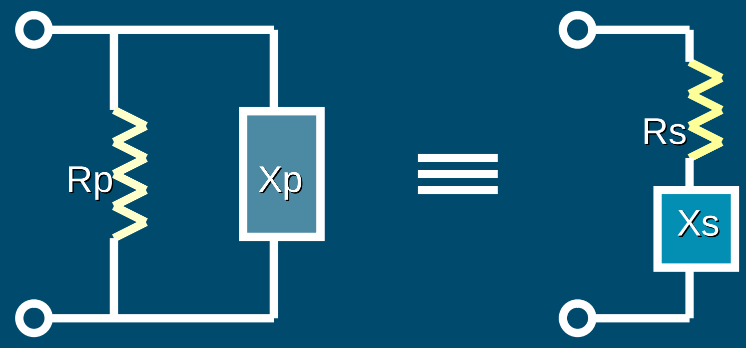
4. Useful Network/Impedance Transformations

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



Let “Q” = Rp/Xp = Xs/Rs

$Rs = Rp/(Q^2+1)$

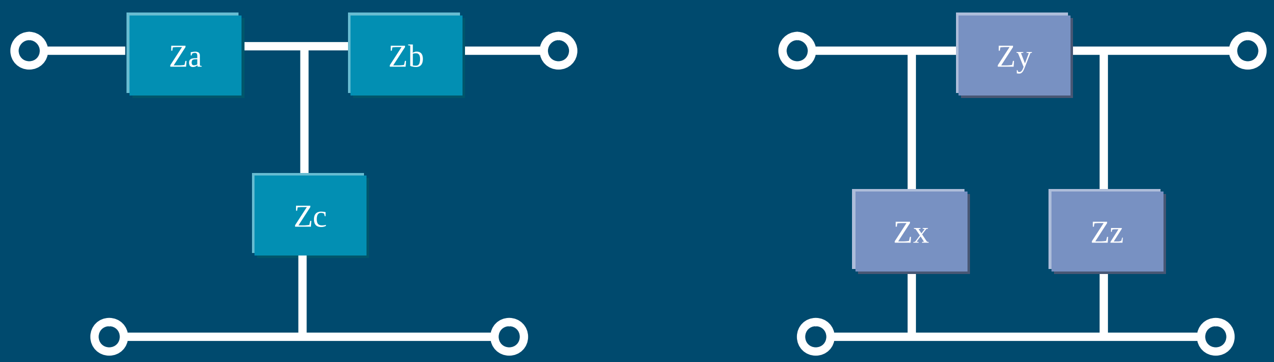
$Xs = Xp(Q^2)/(Q^2+1)$

Example: If Rp = 300 ohms and Xp = j100 ohms at frequency fo, then “Q” = 3 at (and only at fo), this is equivalent to Rs + jXs = 30 + j90

The “Q” is an approximate measure of the bandwidth of the transformation (i.e., BW=fo/Q)

Delta-Star Transformation

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

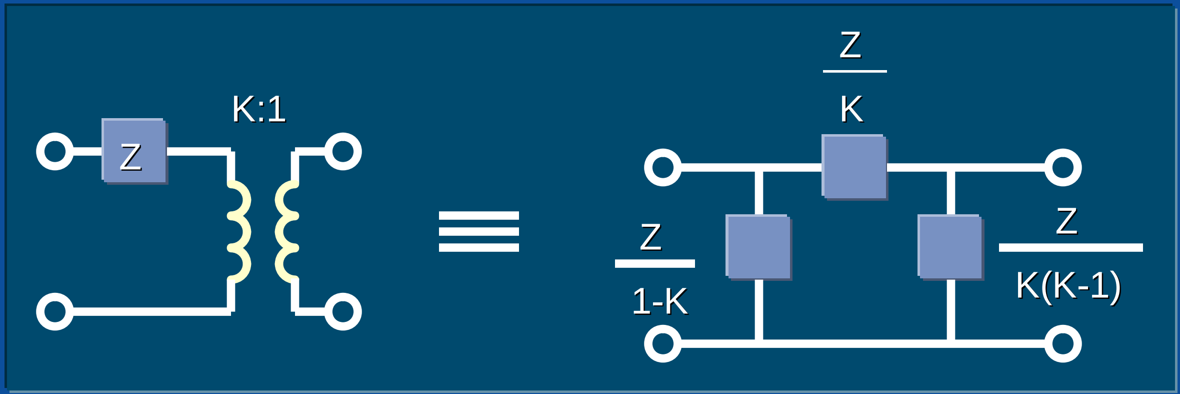


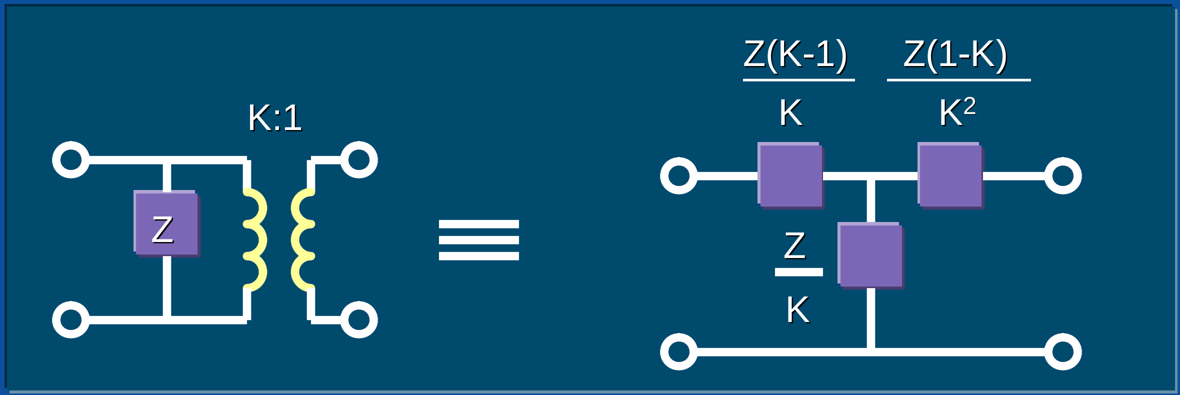
$$\sum ZZ = ZaZb + ZaZc + ZbZc$$

$$Zx = \frac{\sum ZZ}{Zb} \qquad Zy = \frac{\sum ZZ}{Zc} \qquad Zz = \frac{\sum ZZ}{Za}$$

Norton's Transformation

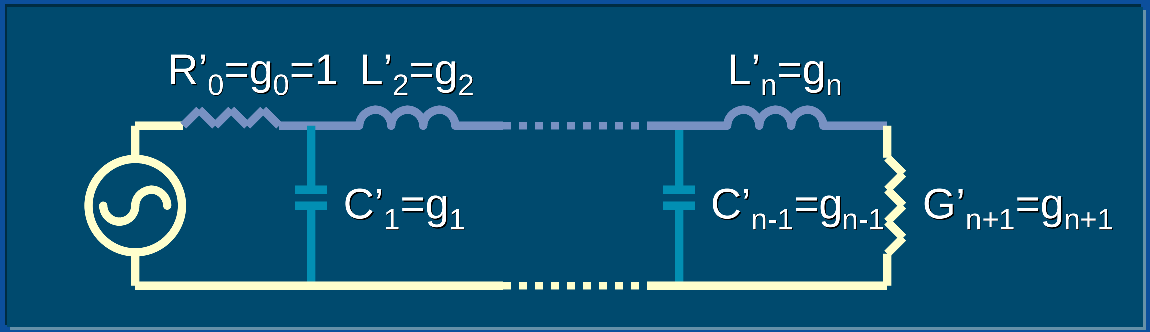
- Very powerful and useful
- Not a single frequency approximation, a true transformation
- Negative value, reactive element can usually be absorbed into existing, adjacent positive value similar reactive element

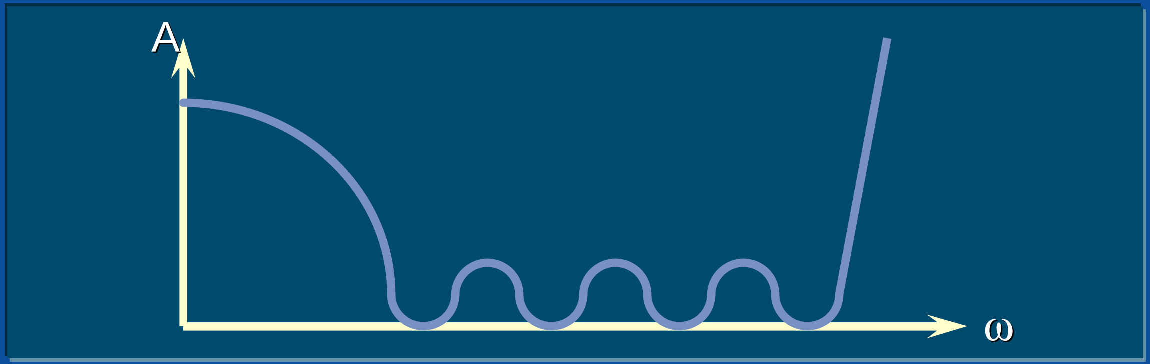




Chebyshev Impedance Transforming Networks [1]

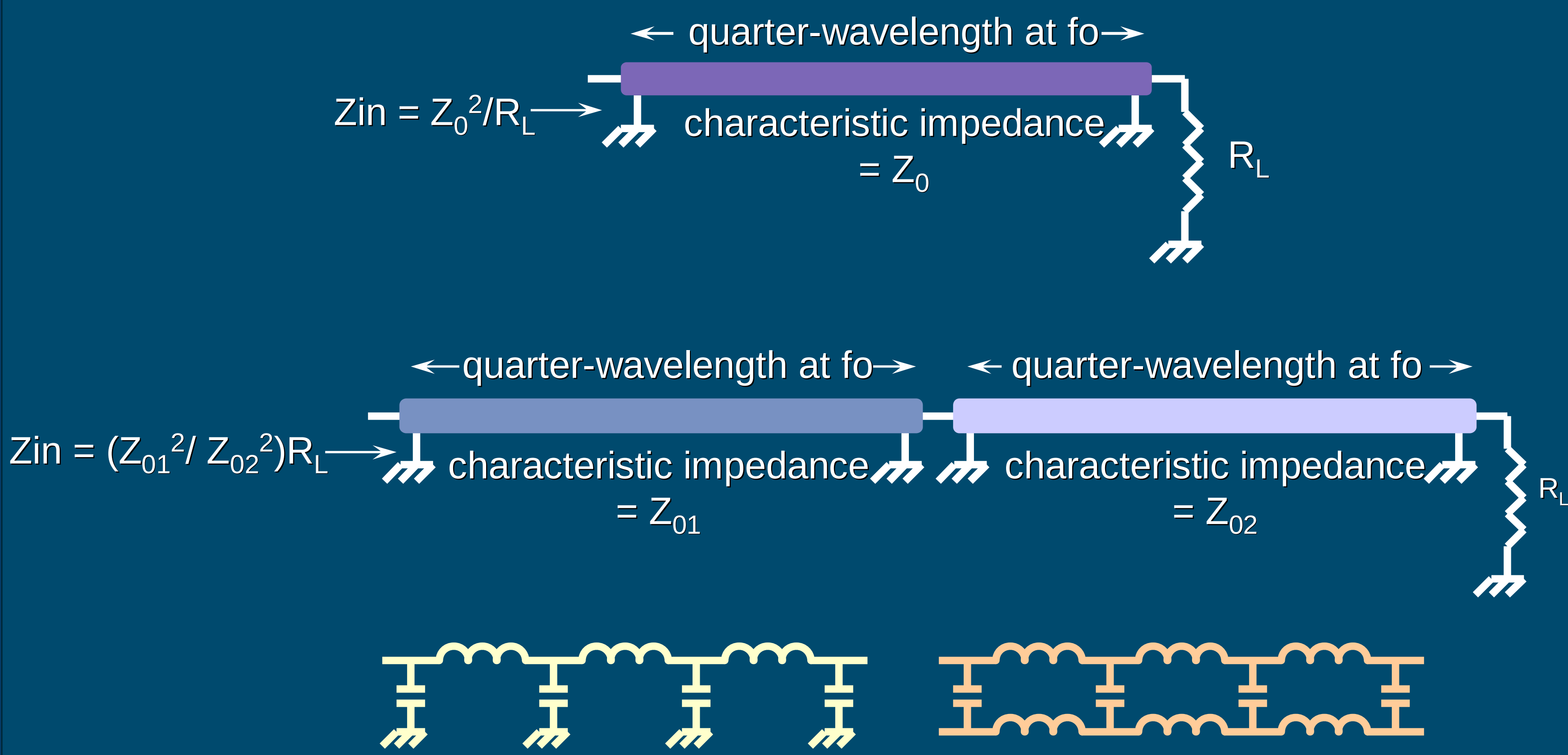
- Tabulated impedance ratios from 1.5:1 to 50:1 and bandwidths from 10% to 100%
- Can be lumped or distributed element





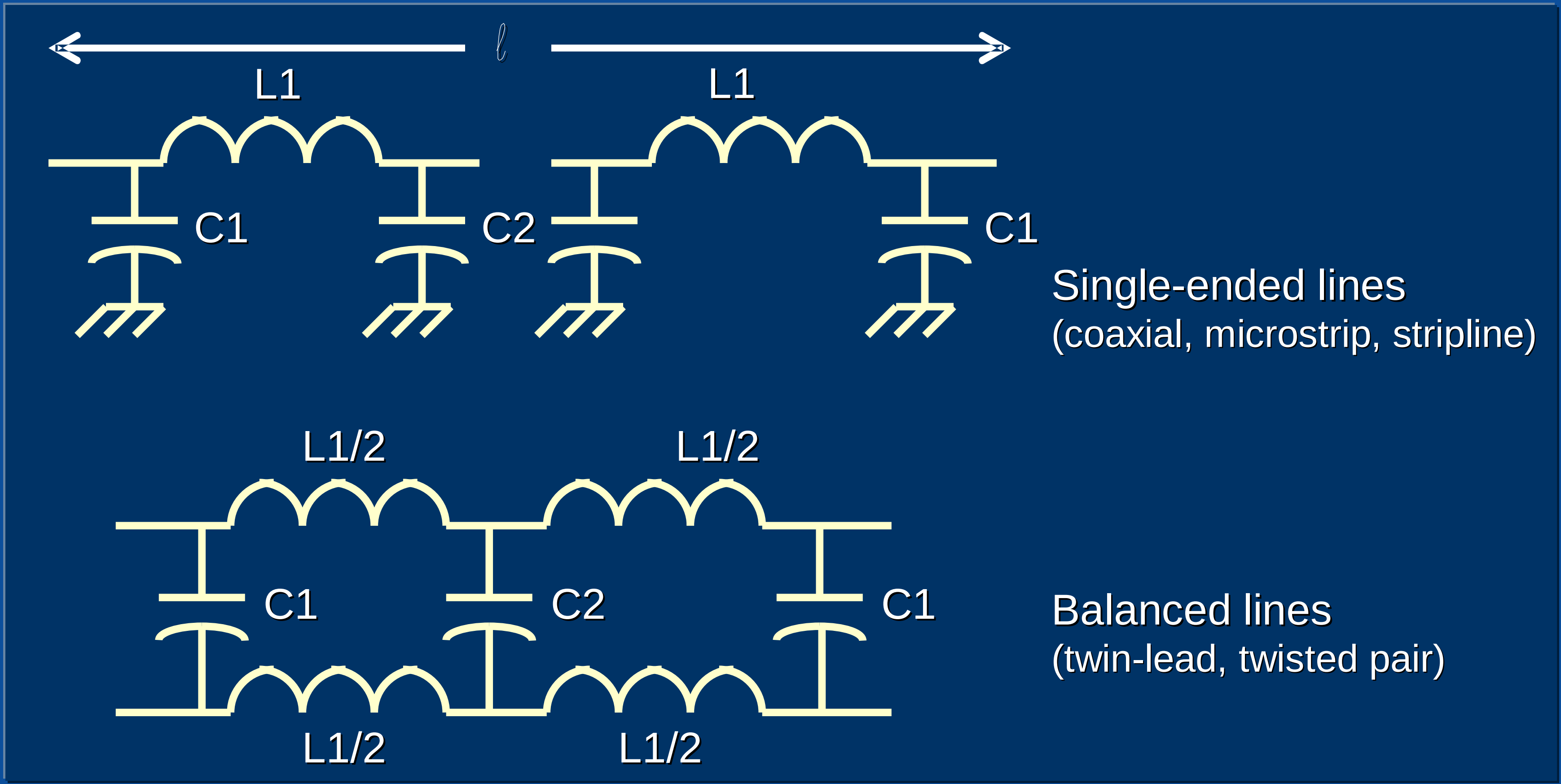
[1] G. L. Matthaei, "Tables of Chebyshev Impedance-Transforming Networks of Low-Pass Filter Form", Proc. IEEE, Vol. 52, No. 8, August 1988, pp. 939-963.

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



Lumped element approximations for a quarter-wavelength lines

Transmission Lines: Lumped Element Approximations



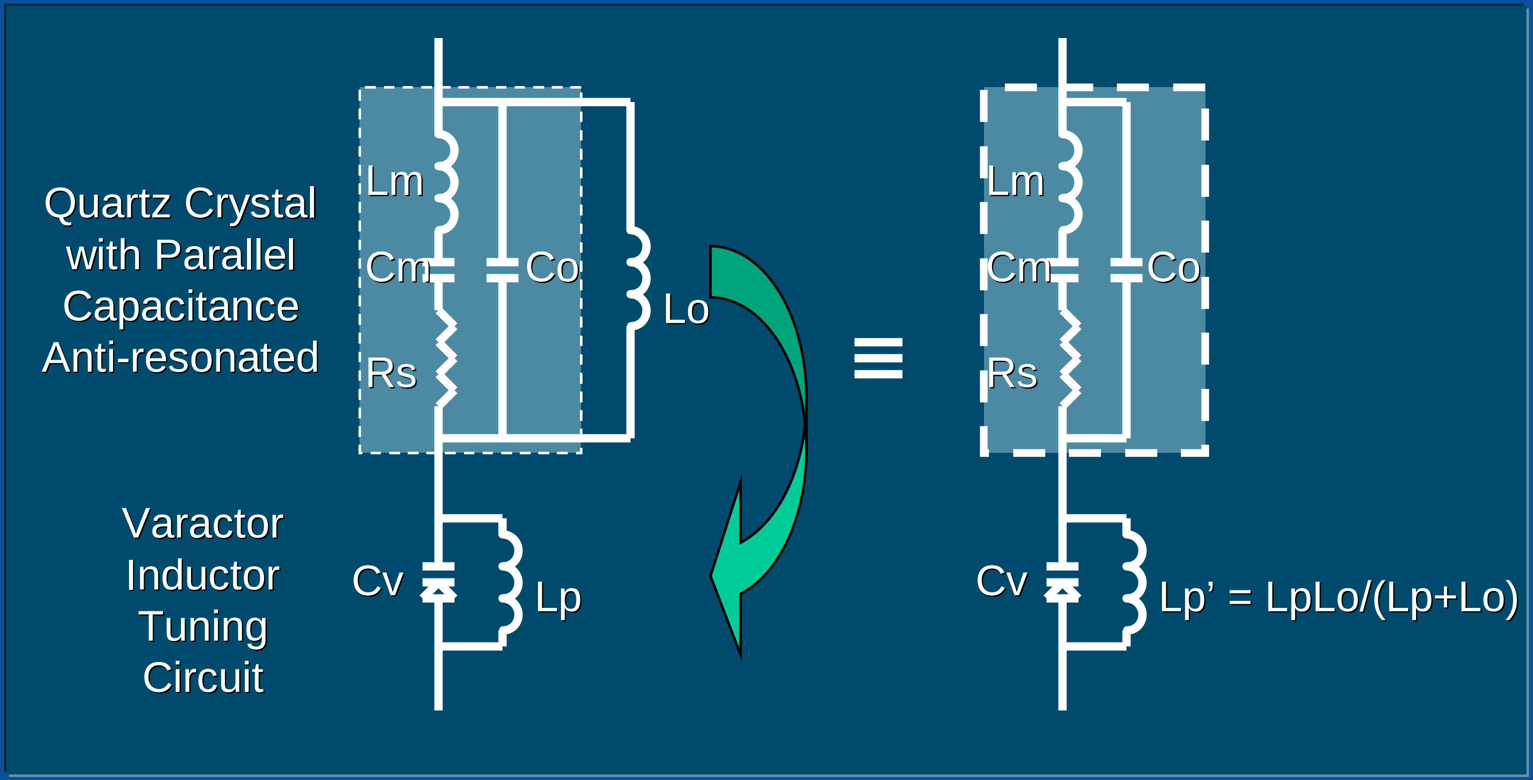
$L_{total} = (\ell/\lambda)(Z_0/f_0)$, $C_{total} = (\ell/\lambda)(1/(Z_0 f_0))$, $L_{total}/C_{total} = Z_0^2$

If the line is considered a series of pi networks, the inner capacitor values are twice that of the end capacitors (i.e., C2=2C1)

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

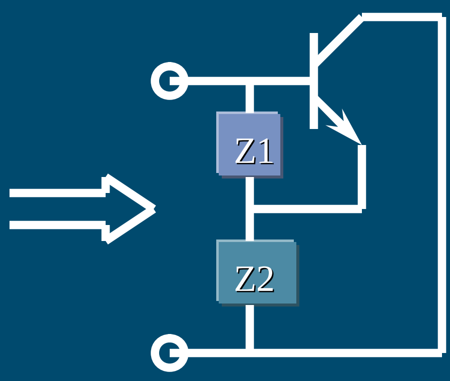


The series resonant frequency of a high Q dipole is unaffected by movement of parallel elements from one portion of the dipole to the other as long as series and parallel resonant frequencies do not approach one another

5. Sustaining Stage Design and Performance

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

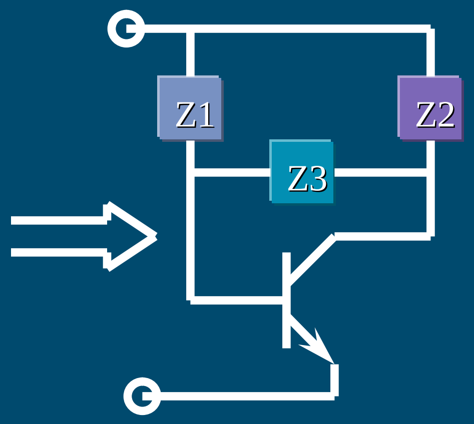
Zin (ideal voltage-controlled current source)
= Z1 + Z2 + gm(Z1)(Z2)
If Z1 and Z2 are reactances, Z1=jX1, Z2=jX2, and
Zin = j(X1+X2) -gm(X1)(X2)
where -gm(X1)(X2) is the negative resistance term



- 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 $\omega = \omega_o = -1/(\omega_o^2 C1C2Rs) + 1/gm$

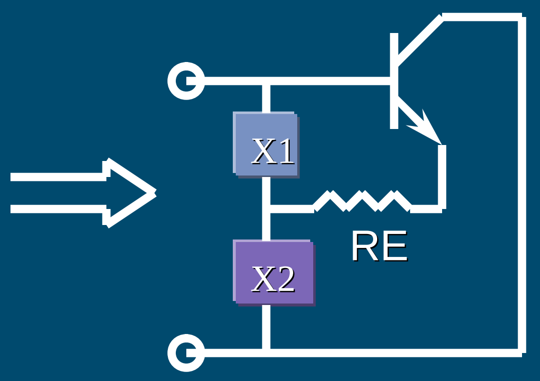


- Normally, capacitors are used as the impedances Z1 and Z2
- Z3 is normally an inductor, and the net resonant resistance of the series combination, Rs, includes that due to the circuit external load resistance as well as the loss in the inductor

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

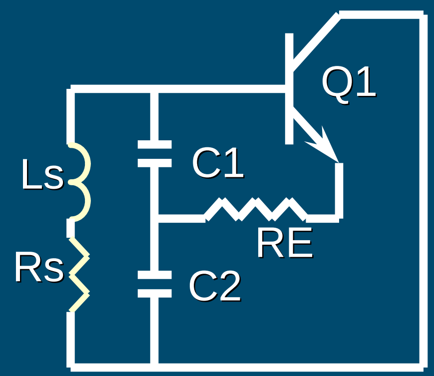
Zin = j(X1+X2) - (X1)(X2)/(RE+1/gm)

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

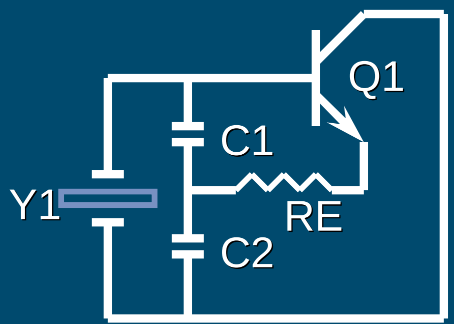


- The addition of RE stabilizes the negative resistance (makes it more dependent on RE then on gm
- In addition, un-bypassed emitter resistance constitutes one method for reducing transistor 1/f PM noise levels

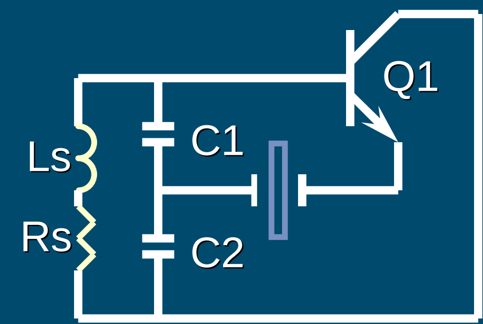
Crystal Oscillators with Crystal Placement in Different Portions of the Circuit



basic oscillator circuit



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



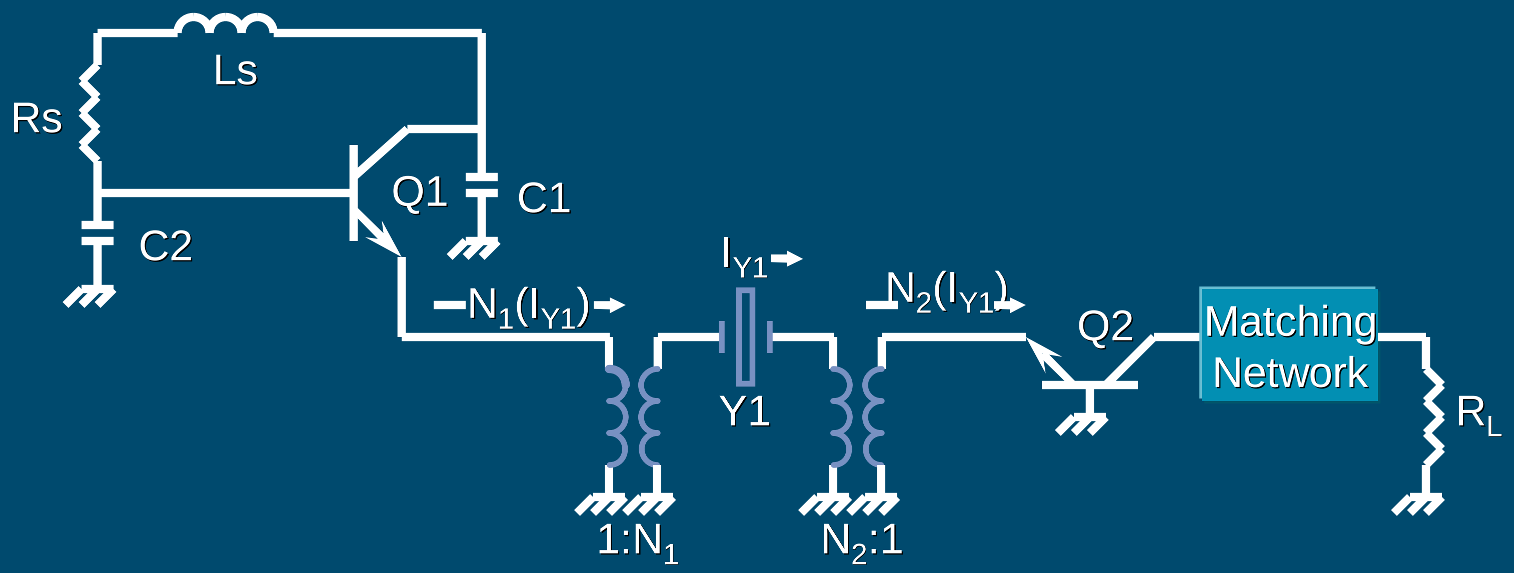
crystal operation at fs
where Z_{Y1} = Rs (i.e., Z=RE)

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 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

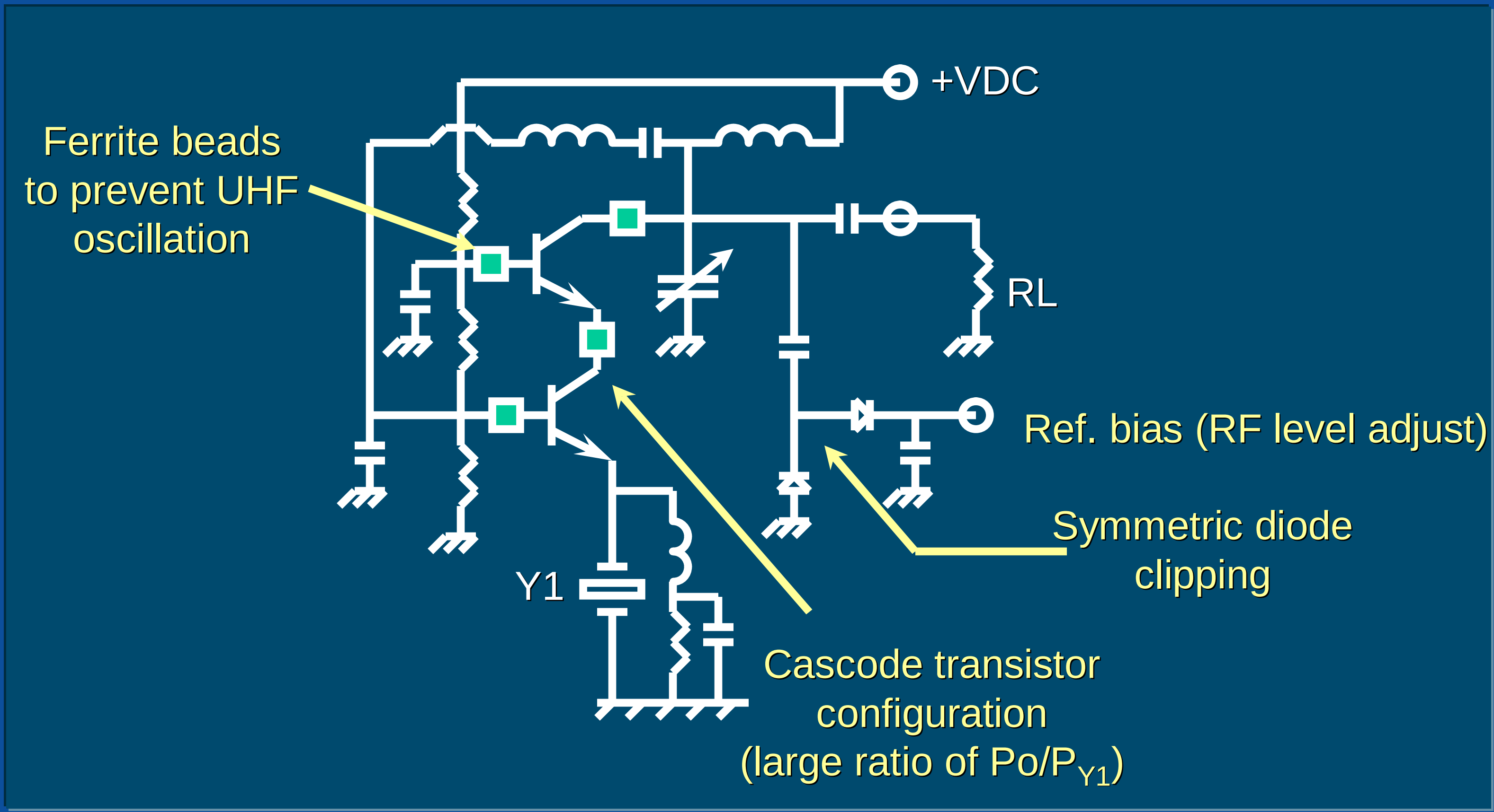
* From the NIST Tutorial on 1/f AM and PM Noise in Amplifiers

Extraction of the Oscillator Signal Through the Resonator



Transformer sometimes used to step up current into Q1,Q2

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)

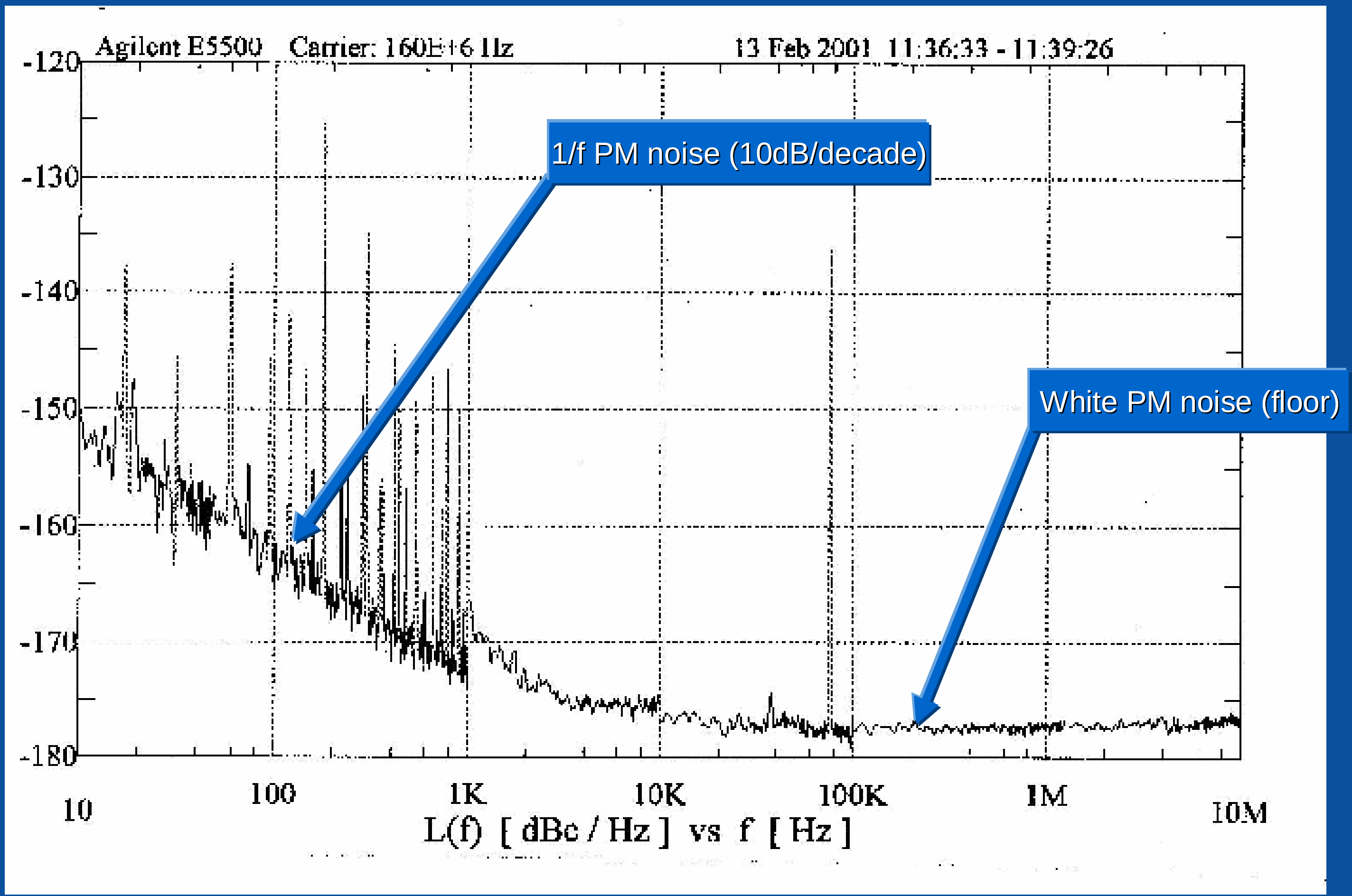
Disadvantages

- 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.

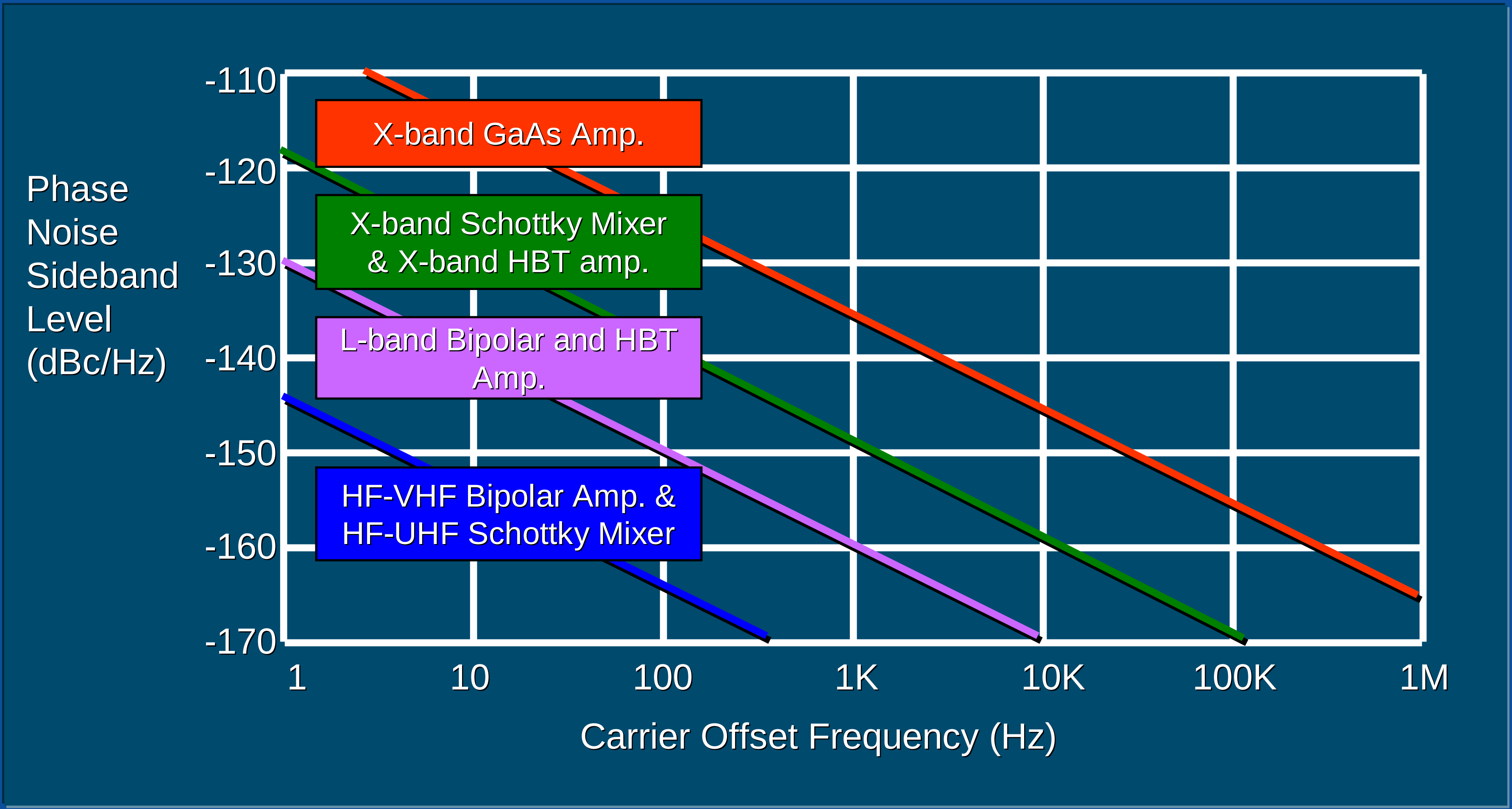
Advantages of Modular Amplifier Sustaining Stages

- 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



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 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

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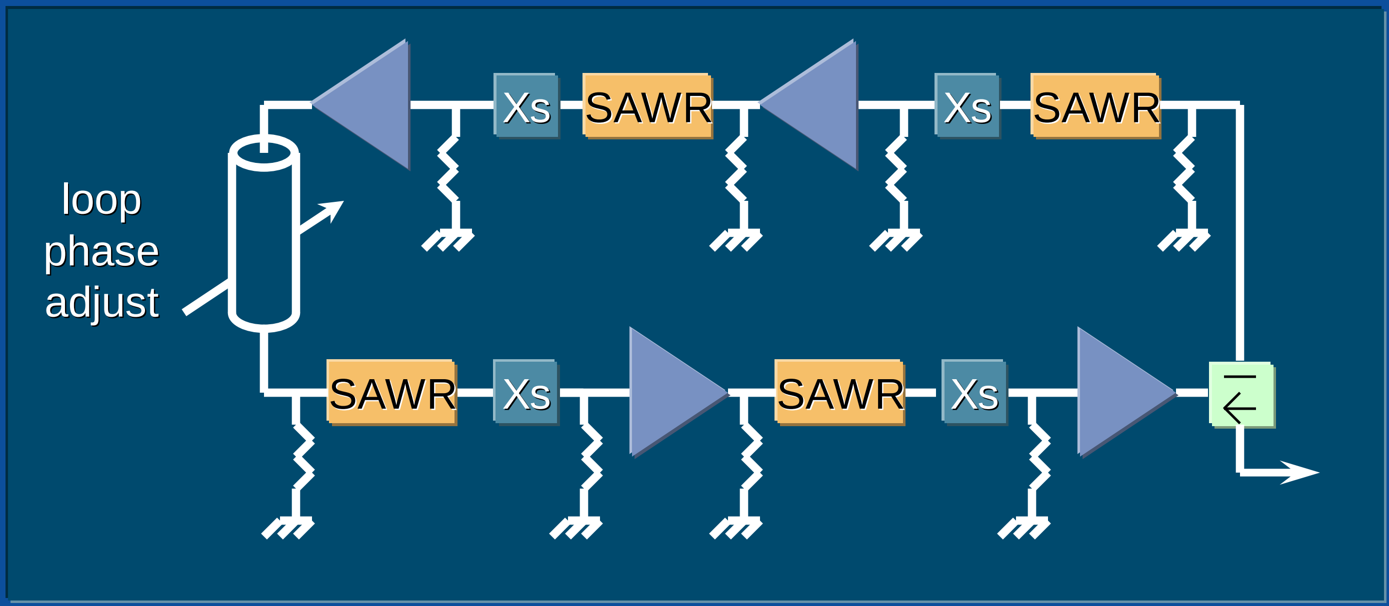
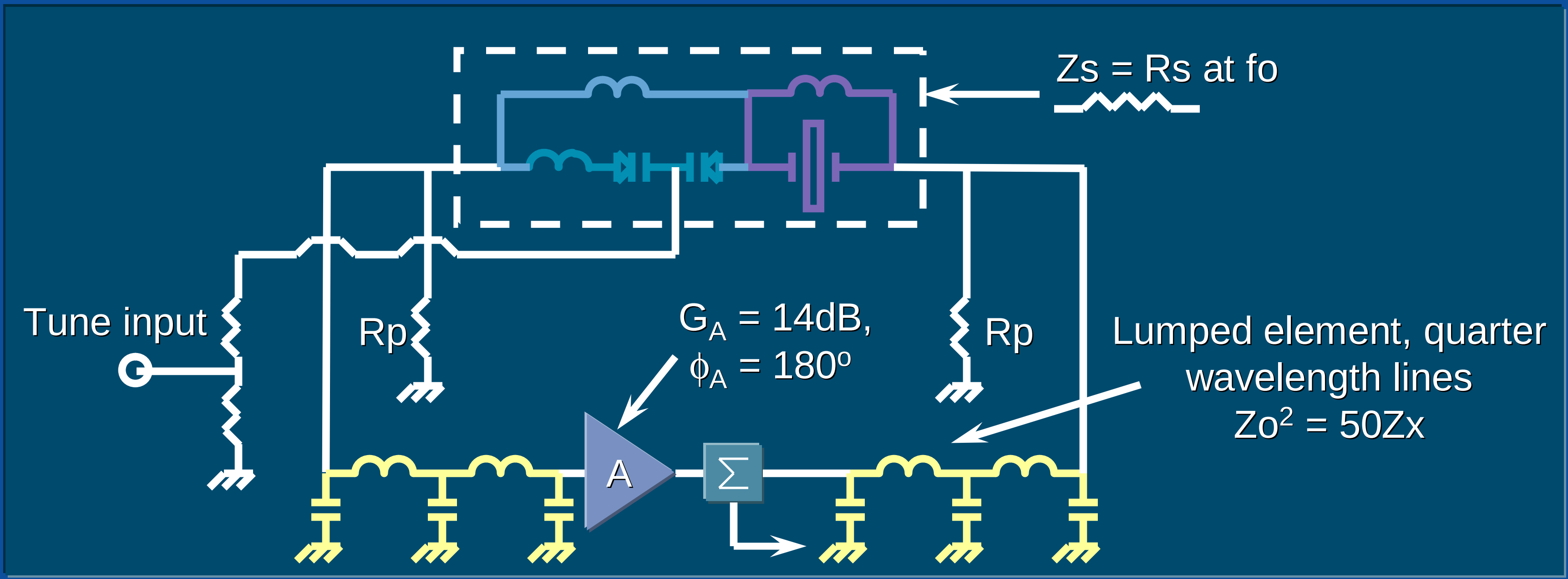
Modular Amplifier Oscillator Design Example: Low Noise, SAWR Oscillator



- Xs = 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 fm=100Hz at fo=320MHz
- Requires accurate tracking between resonators over time and temperature

Modular Amplifier Oscillator Design Example: Low Noise, HF Oscillator



- 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

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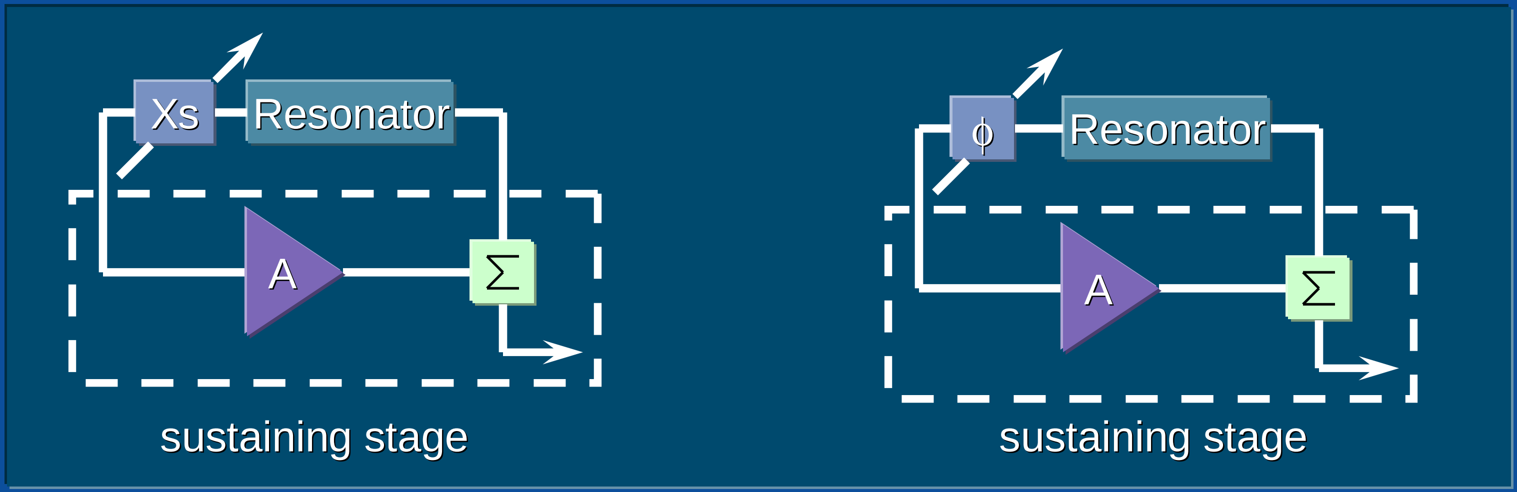
6. Oscillator Frequency Adjustment/Voltage Tuning

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

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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

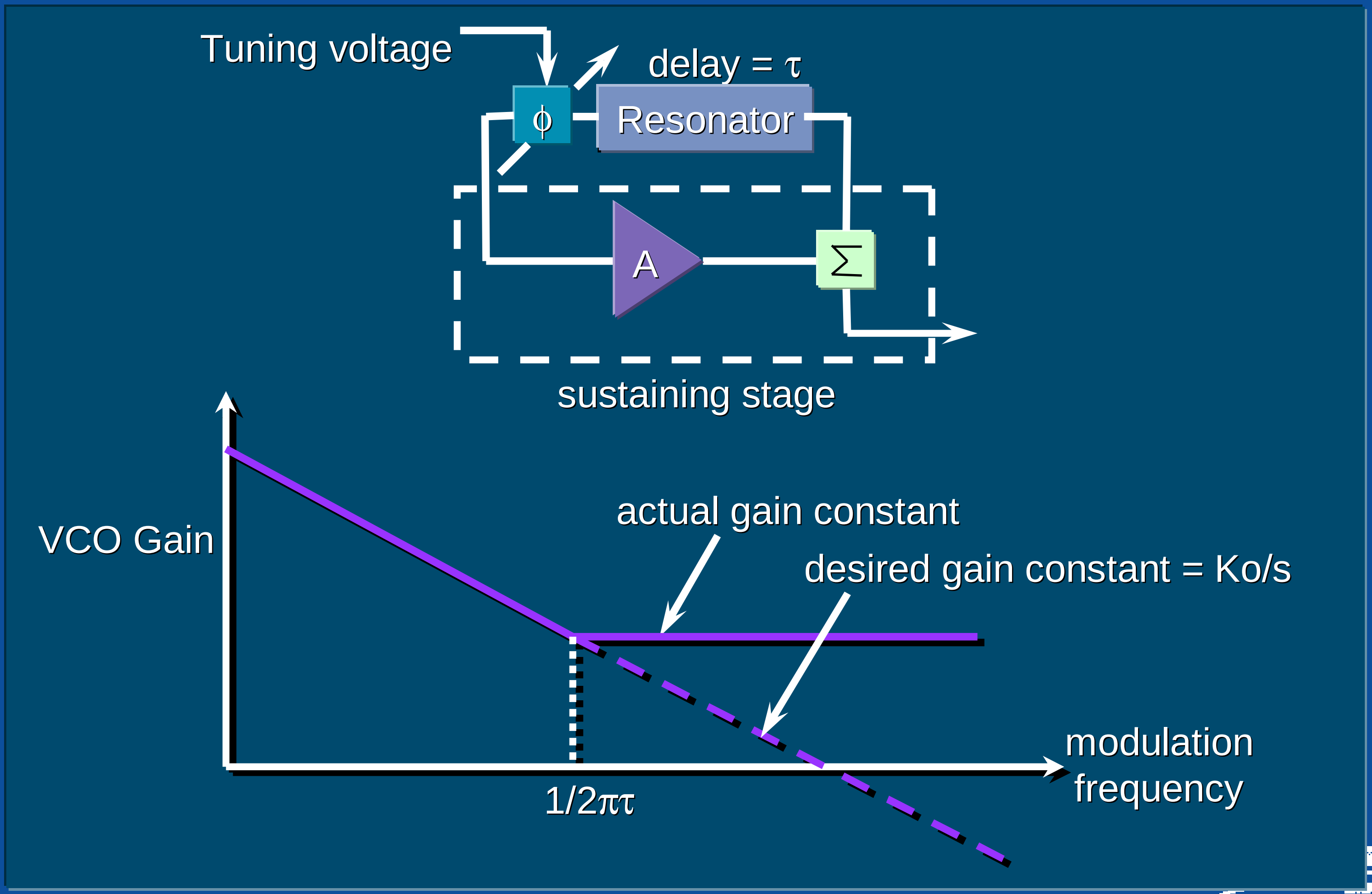
Carrier signal moves within the resonator transmission response pass-band; tuning range is restricted to less than the passband width

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

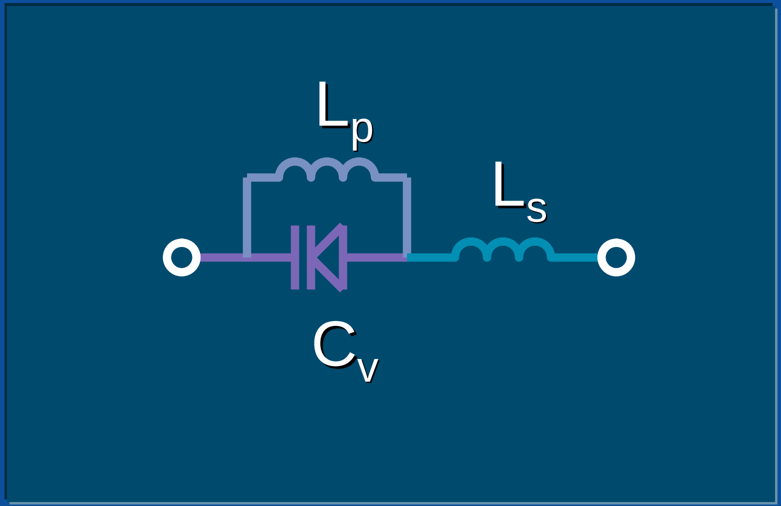
- Modulation frequency response affected by placement of phase shifter



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 $\gamma = 0.5$
- 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 $0.375\omega_o Lp/(vo+\phi)$

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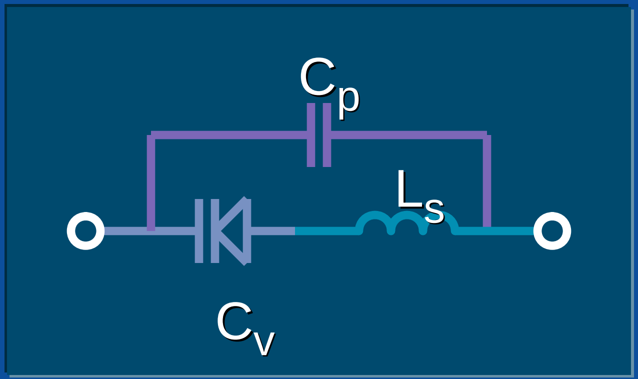
Linear Susceptance vs Voltage



- For near-linear susceptance vs voltage using abrupt junction varactor diode, $1/(LsCvo) = \omega_o^2/3$ where Cvo is the varactor diode capacitance at the band center voltage = Vo
- For zero susceptance at the band center tuning voltage, Cp = Cvo/2

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

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

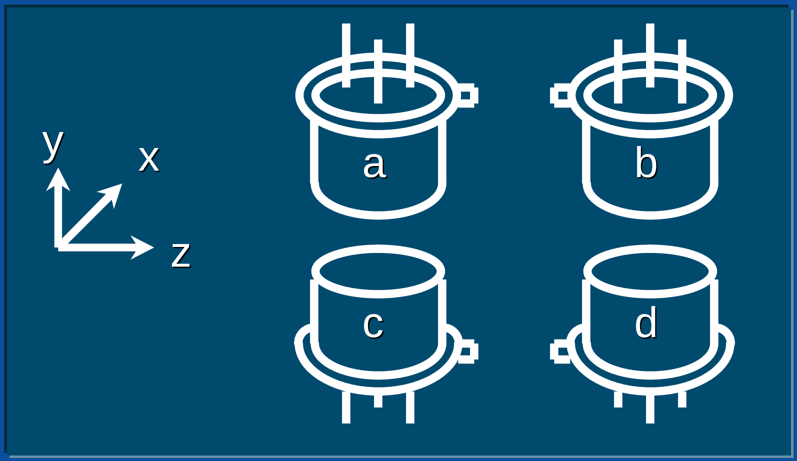
- A 100MHz crystal oscillator can exhibit a phase noise sideband level at 1KHz carrier offset frequency of -163dBc/Hz.
- The fractional frequency instability is Sy(f=1000Hz) = $1X10^{-26}$/Hz.
- The corresponding phase instability, $S\phi(f)$, is $1X10^{-16}$ rad^2/Hz.
- The crystal vibration level that 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
- 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



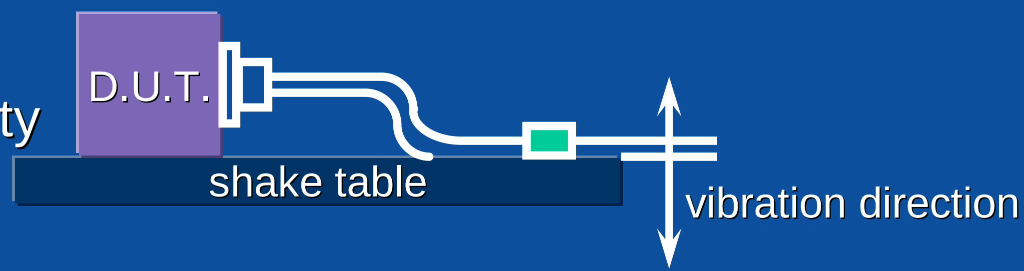
- Crystals connected electrically in series
- 5:1 reduction in vibration sensitivity magnitude has been achieved using four crystals

Measurement of Oscillator/Resonator Vibration Sensitivity

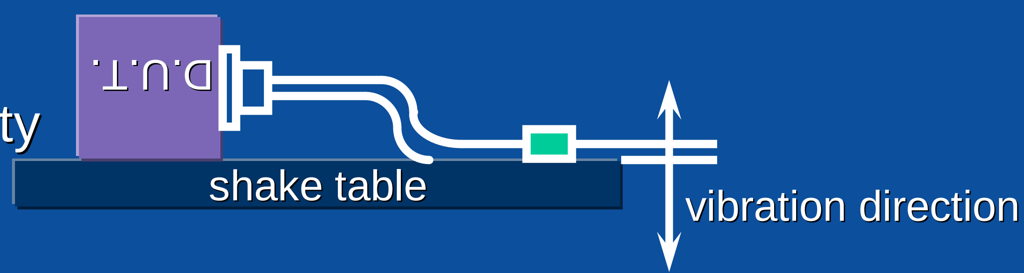
- Entire oscillator or resonator alone can be mounted on a shaker for determination of vibration sensitivity.
  - Resonator vibration sensitivity measurements can be made with the resonator connected to the oscillator sustaining stage or connected in a passive phase bridge.
- The effects of coaxial cable vibration must be taken into account, especially for measurement of devices having very small values of vibration sensitivity.
  - 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
$= \Gamma_{COAX} + \Gamma_{DUT}$



Measurement #2
Overall vibration sensitivity
$= \Gamma_{COAX} - \Gamma_{DUT}$



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)

8. 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.

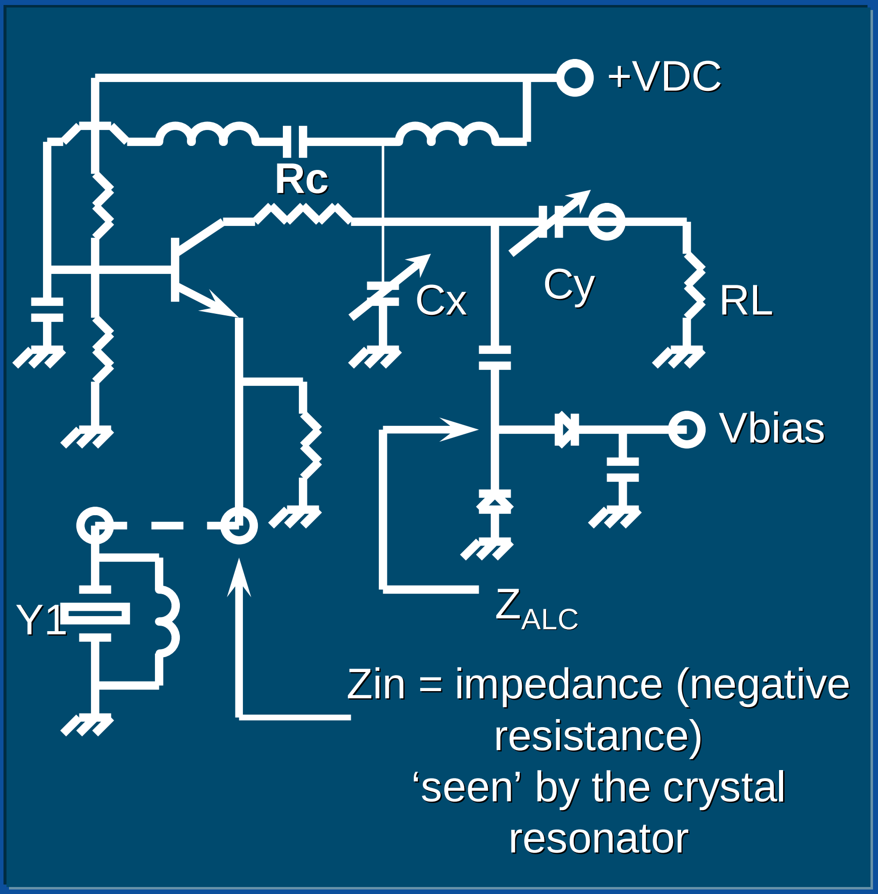
CAD Small Signal Analysis of Oscillator Circuits

- 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

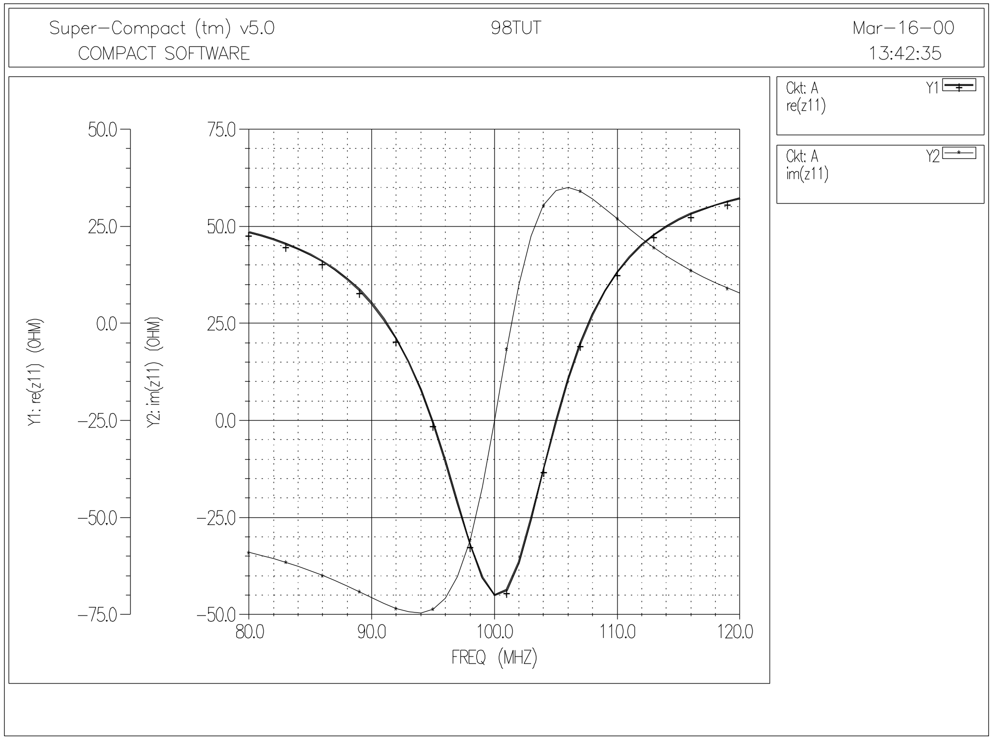
- CAD circuit simulation can (and should) include circuit analysis at out-of-band frequency regions to make sure conditions for oscillation are only satisfied at the desired frequency.
- Frequency bands where undesired resonator resonant responses occur (i.e., unwanted crystal overtone resonances) should 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



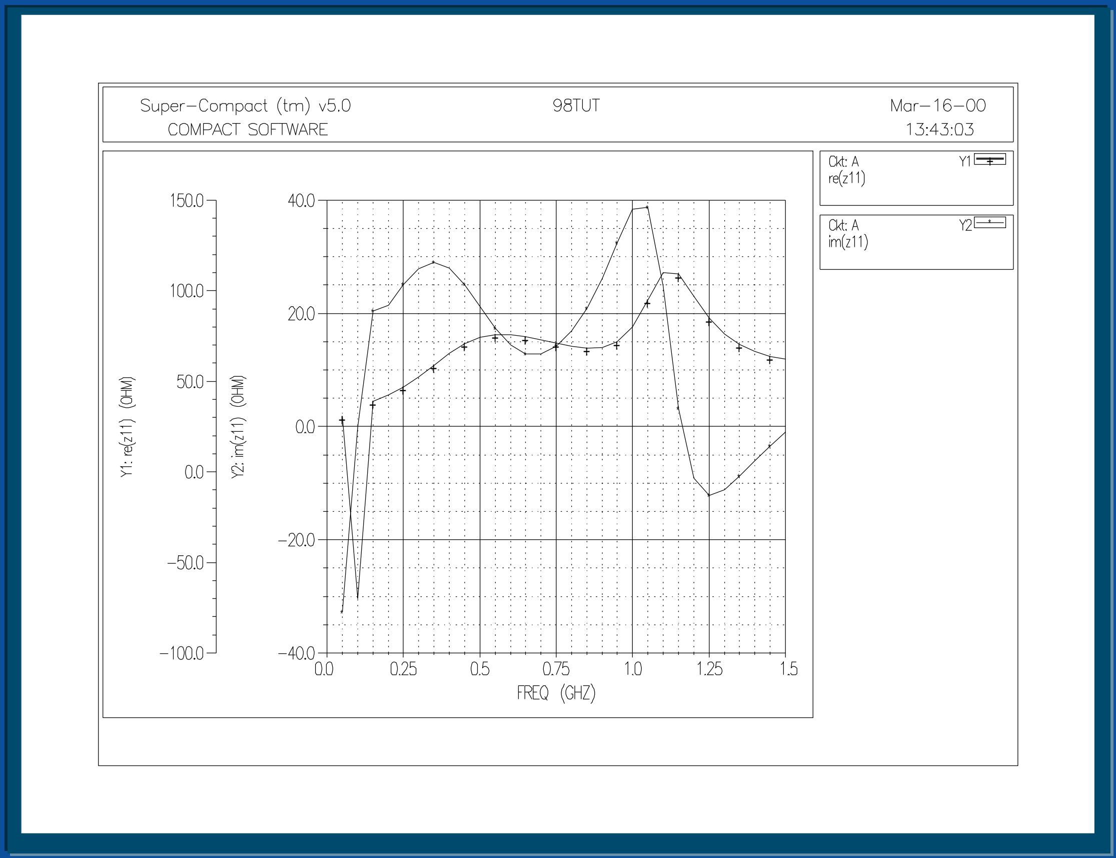
- Cx and Cy values optimized to provide Zin = -70 + j0 at 100MHz
- Zin calculated from 50MHz to 1GHz to insure negative resistance is only generated over a small band centered at 100MHz (note use of Rc)
- Large signal condition (where the negative resistance portion of Zin drops to 50 ohms = crystal resistance) simulated by reducing the ALC impedance value

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



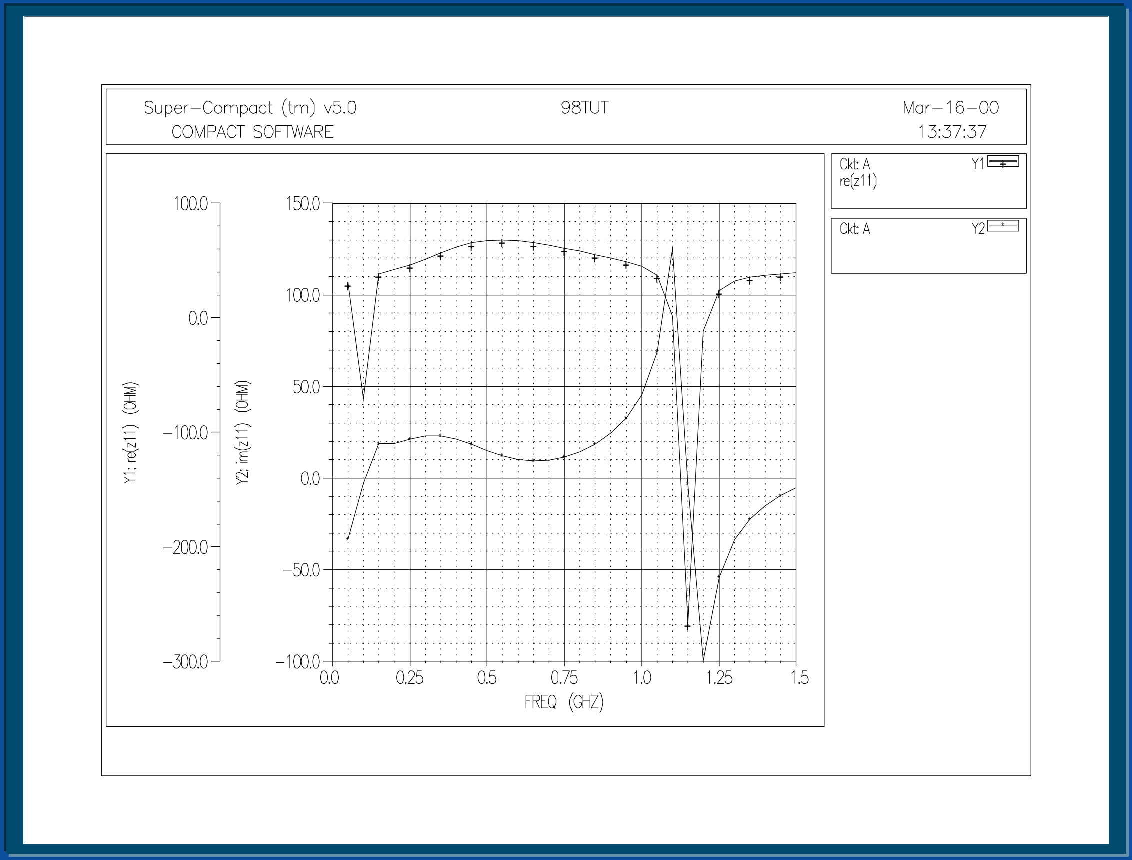
- Zin = - 70 + j0 at 100MHz

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



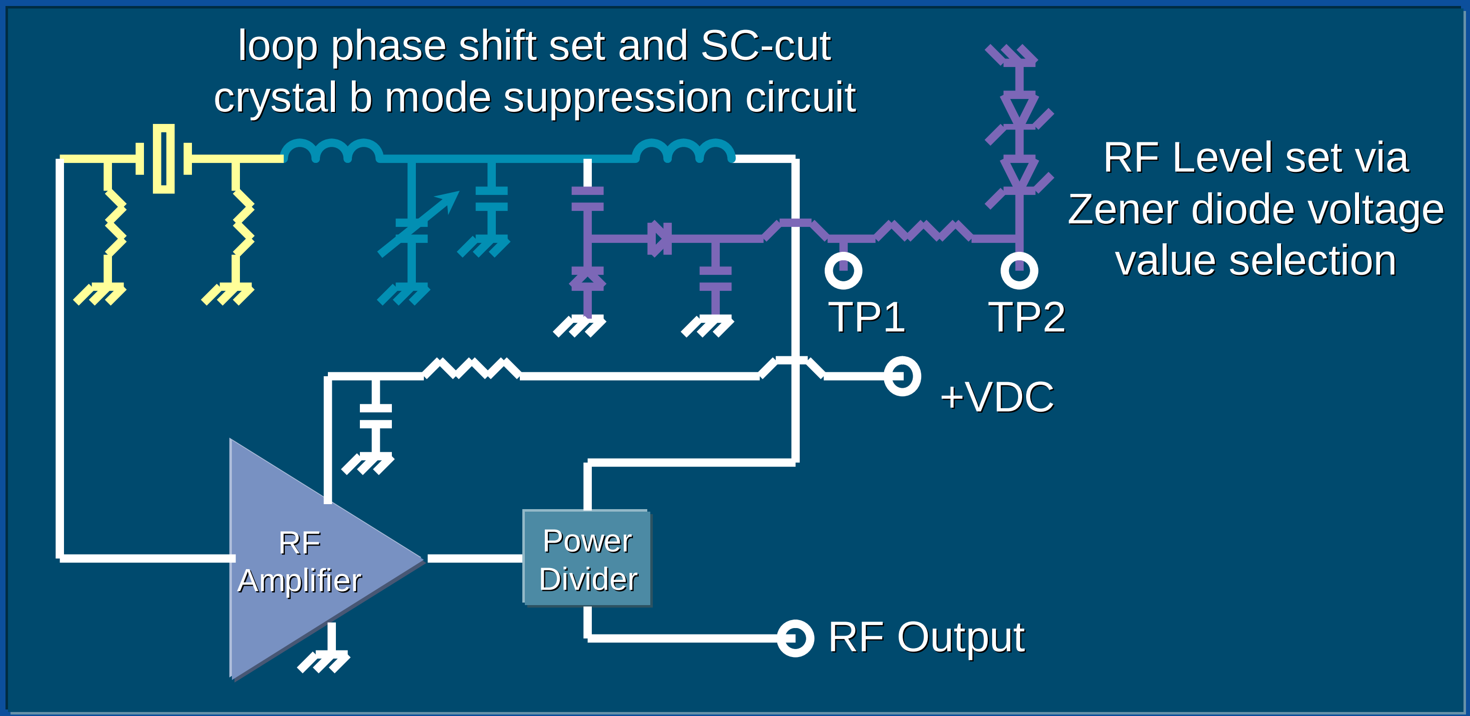
- 33 ohm collector resistor installed in the circuit
- Note that the real part of the impedance remains positive everywhere except at the desired frequency band at 100MHz
- This fact indicates the circuit will only oscillate at the desired frequency

Results of 100MHz Oscillator Sustaining Stage Circuit Simulation



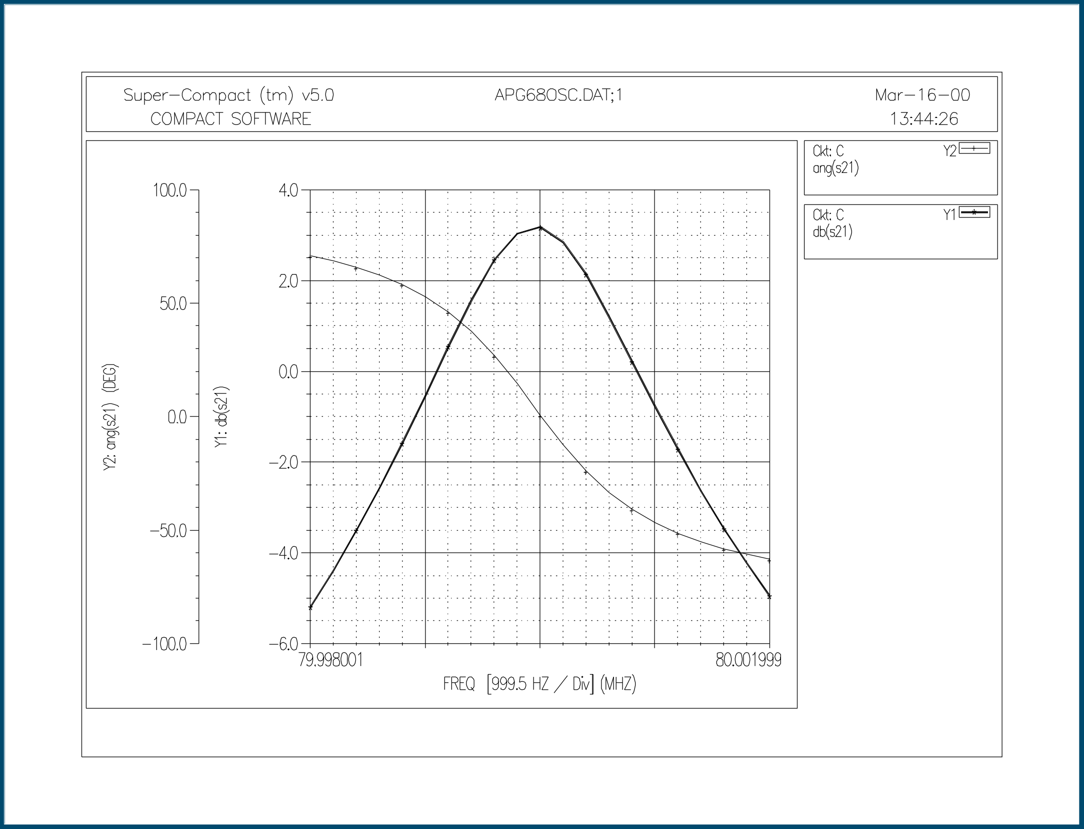
- 50MHz to 1.5GHz; collector resistor (Rc) *removed*
- Note that the real part of the impedance becomes highly negative1.15GHz
- This fact points to a probable circuit oscillation at/near 1.1GHz

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

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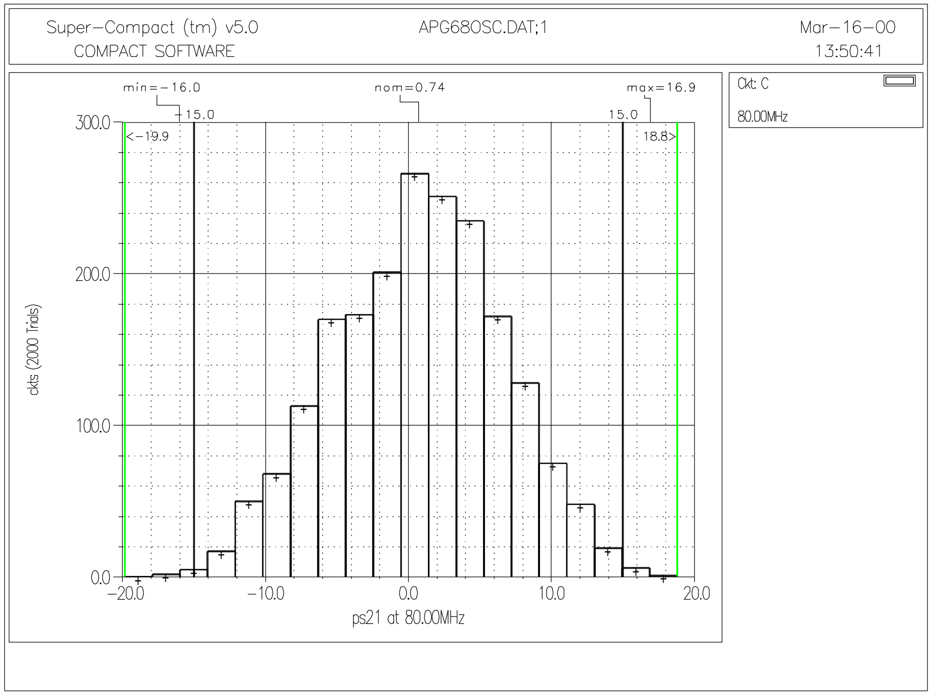
80MHz Oscillator Circuit Simulation

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 Sf(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.

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).

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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

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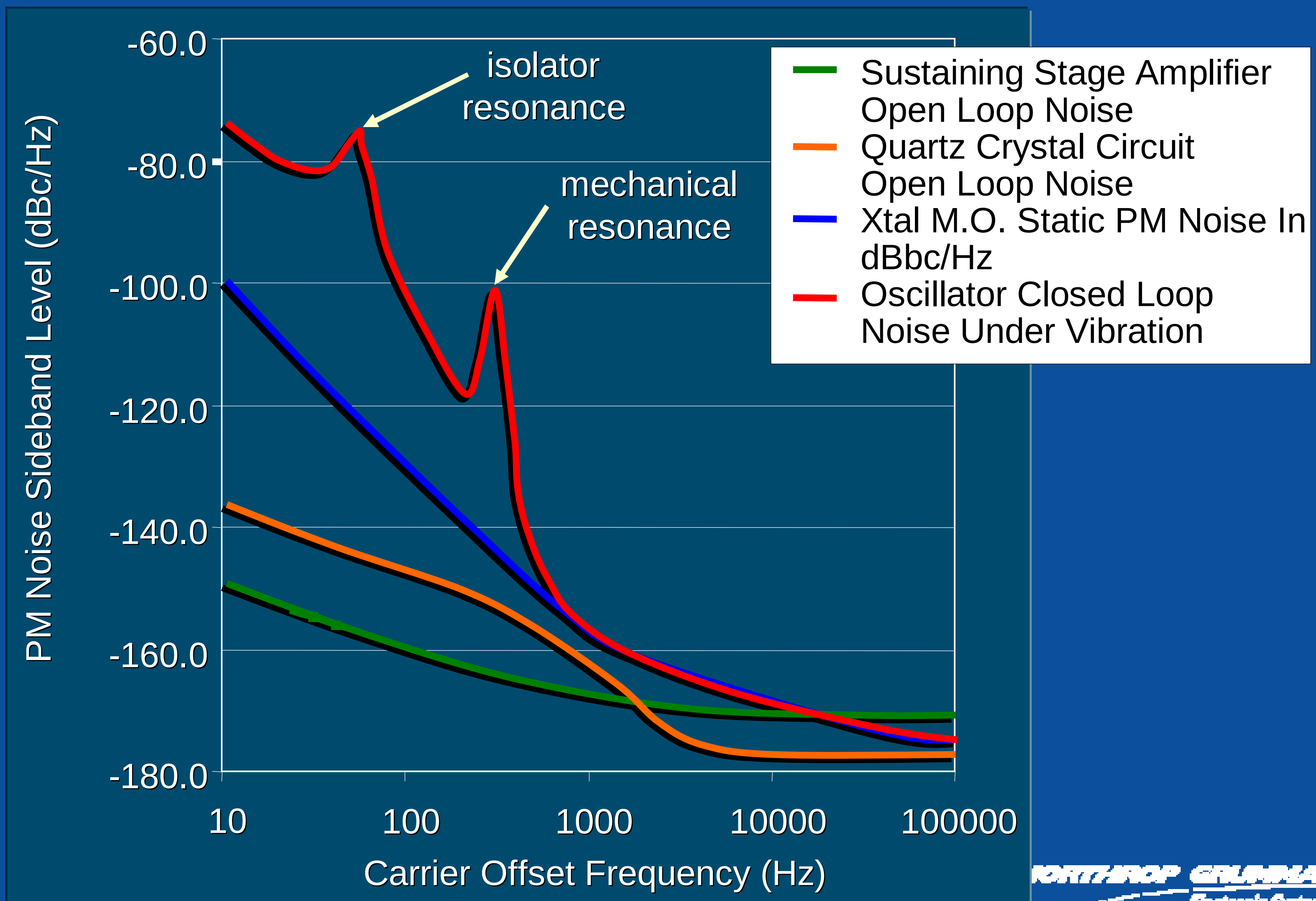
Oscillator Noise Modeling - Vibration

- 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)

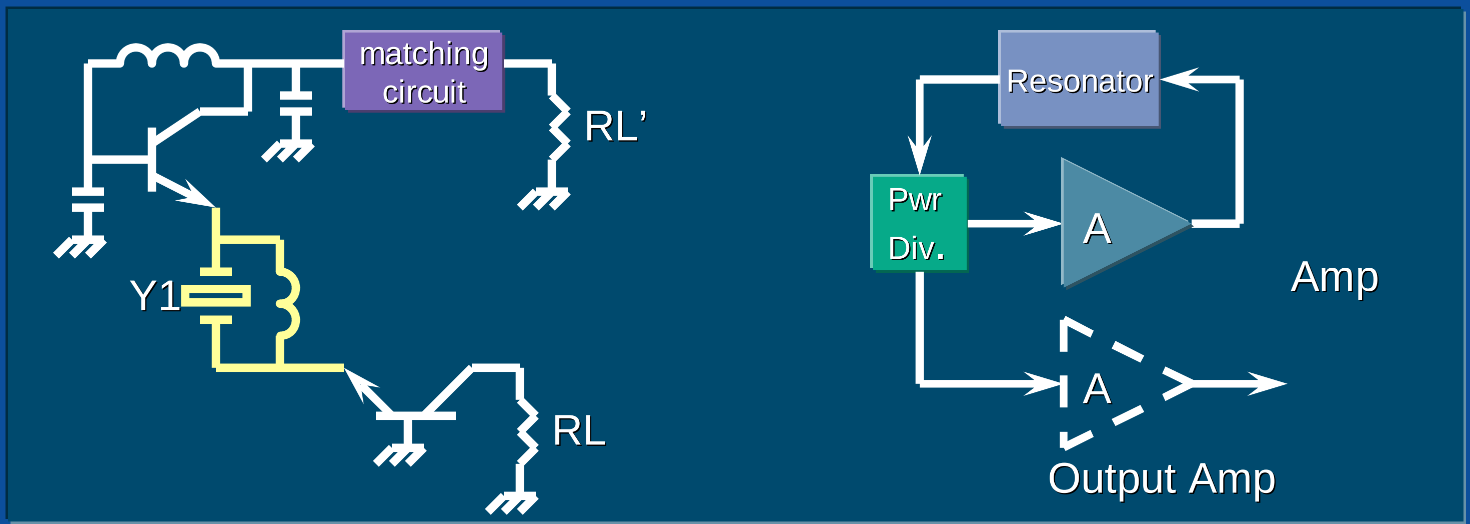
VHF Crystal Oscillator



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

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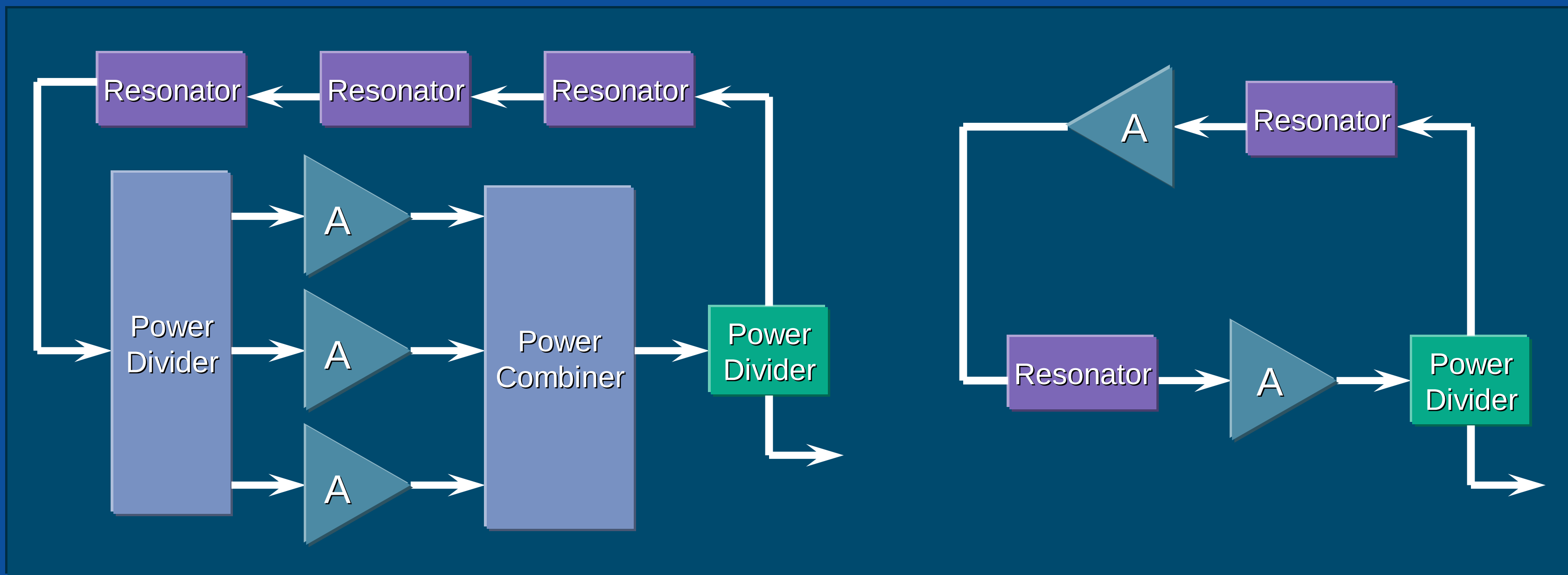
Methods to Reduce Noise Internal to the Oscillator Circuit (continued)

- 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

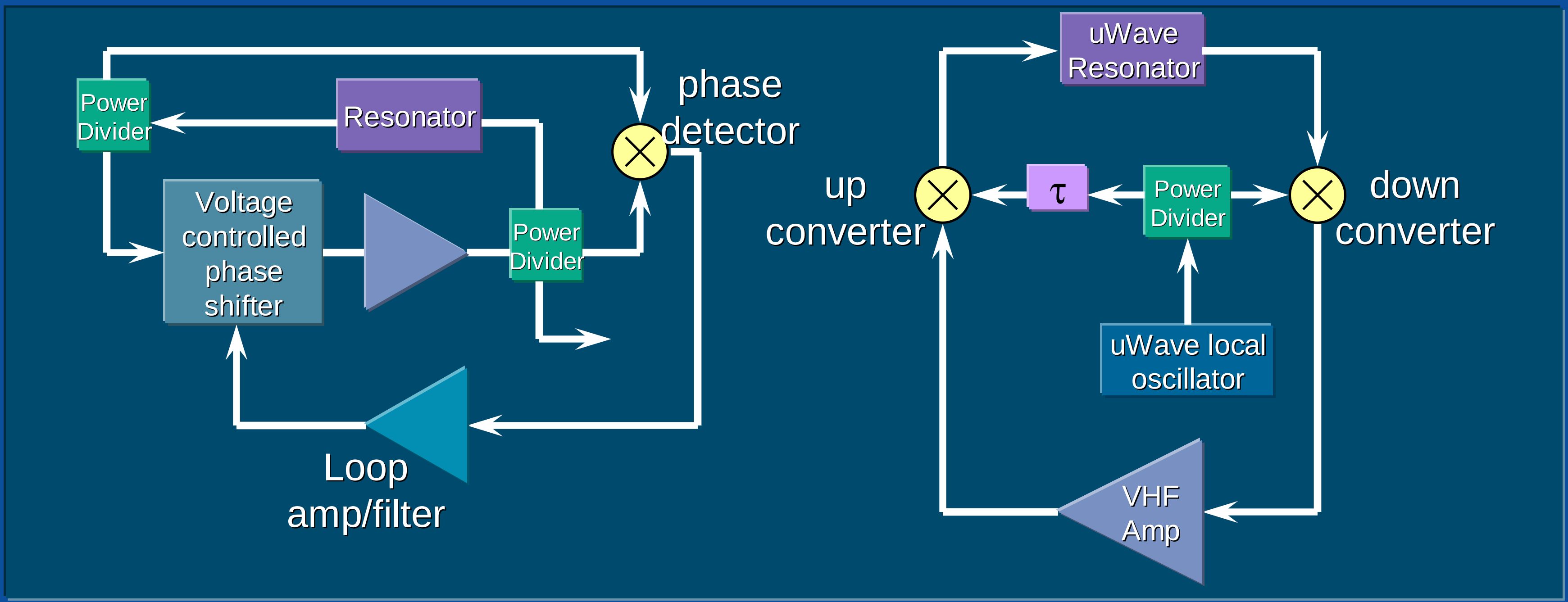


- Noise de-correlation in amplifiers and/or resonators
- Cascaded amplifier-resonators to increase loop group delay

Additional Methods for Reducing Noise Internal to the Oscillator Circuit

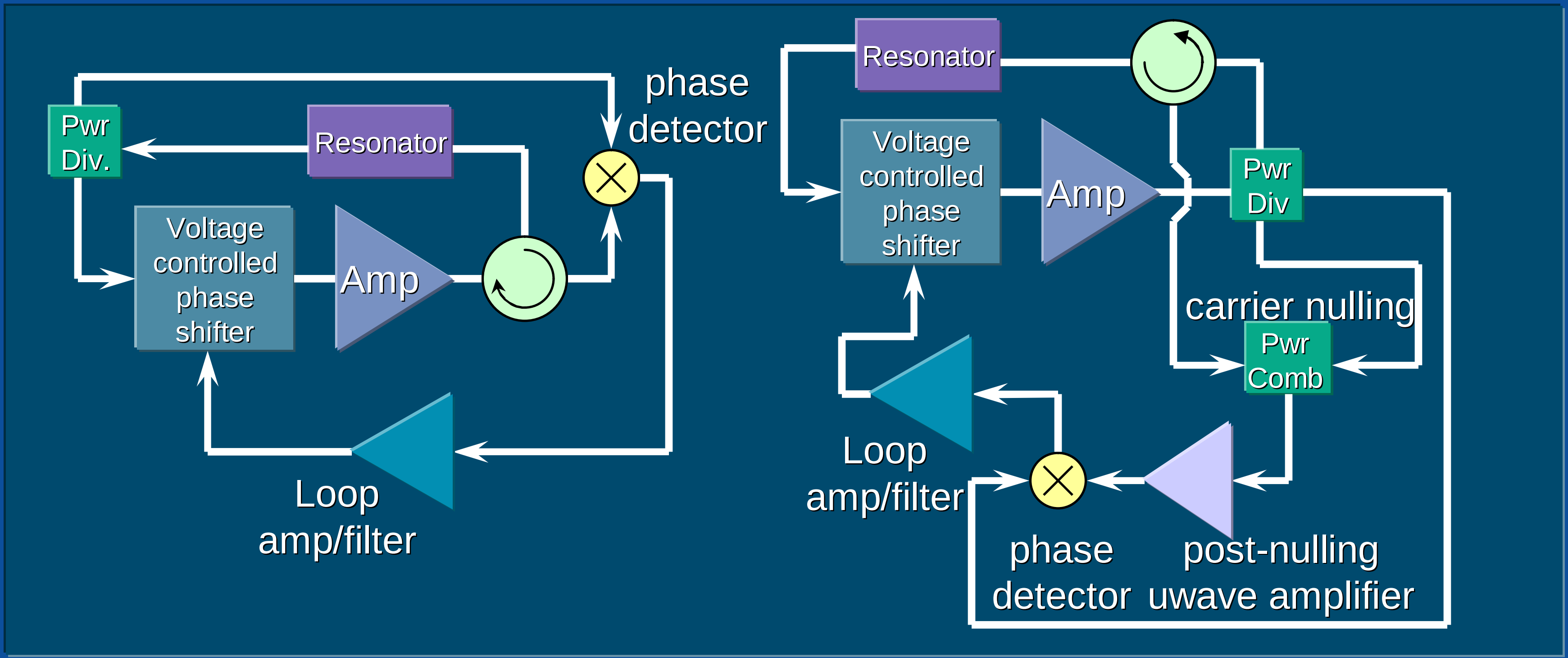
- Consider sustaining stage amplifier noise reduction via:
  - noise detection and base-band noise feedback (to phase and amplitude modulators) or
  - feed-forward noise cancellation

Example: Noise Reduction Techniques



- Wide-band noise feedback to reduce sustaining stage amplifier 1/f PM noise
- VHF delay = τ
- Double frequency conversion:
  - Sustaining stage implementation at VHF using a low 1.f PM noise amplifier

Example: Additional Noise Reduction Techniques



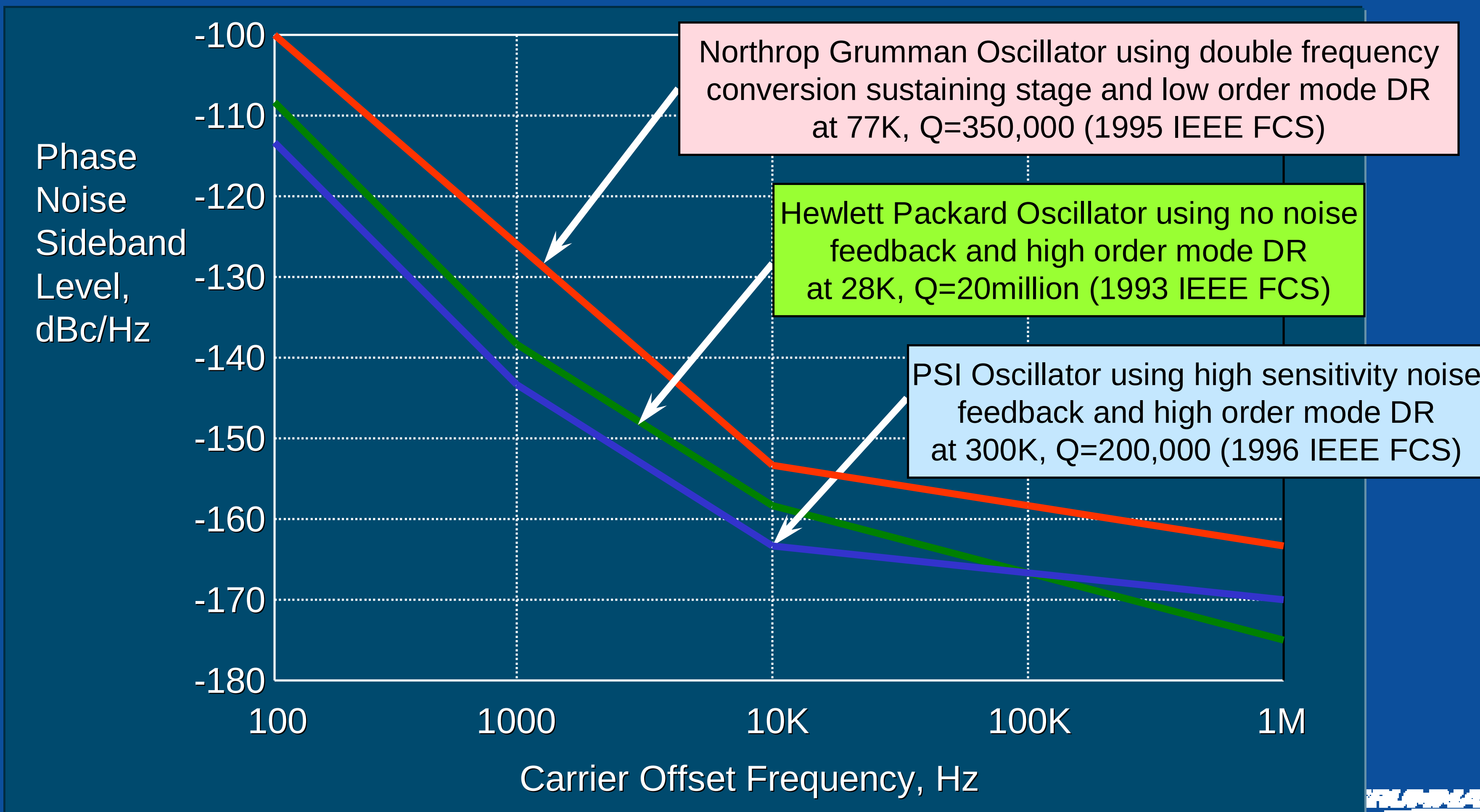
Use of resonator response to increase phase detector sensitivity

(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

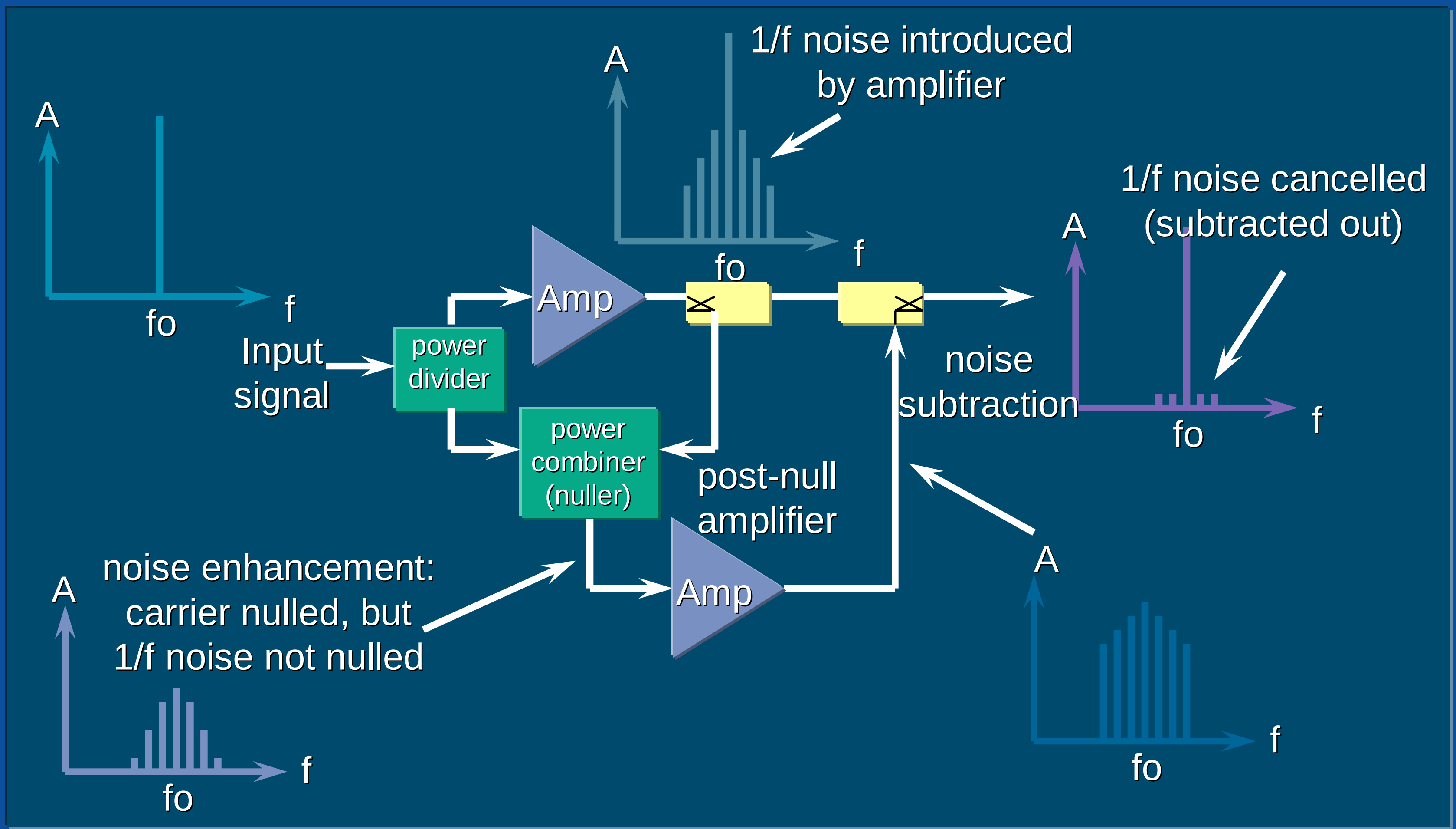
- Lower Noise with 60 times lower Q



*Amplifier Noise Reduction via Feed-forward Cancellation**

(no noise down-conversion to base-band)

*amplifier operated linearly

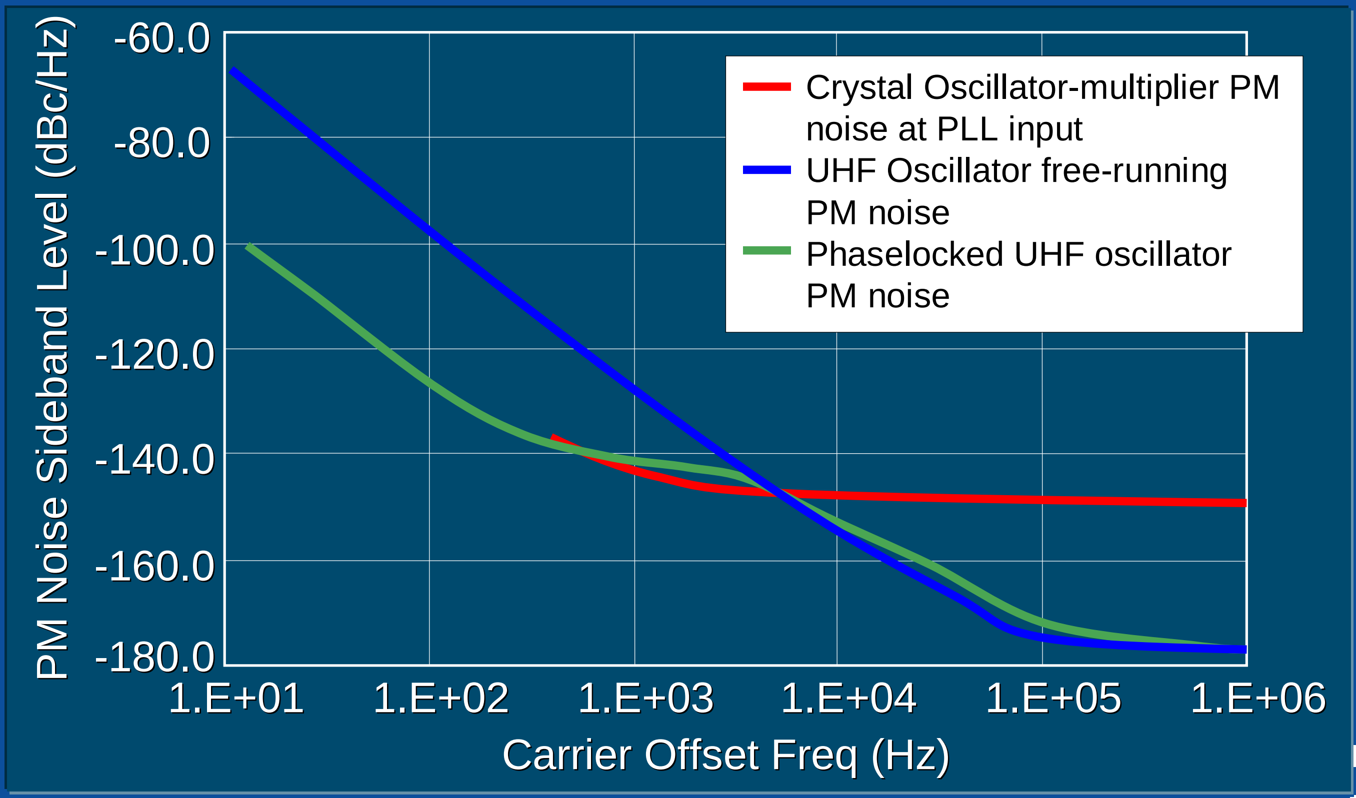


Methods to Reduce Noise External to the Oscillator Circuit

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

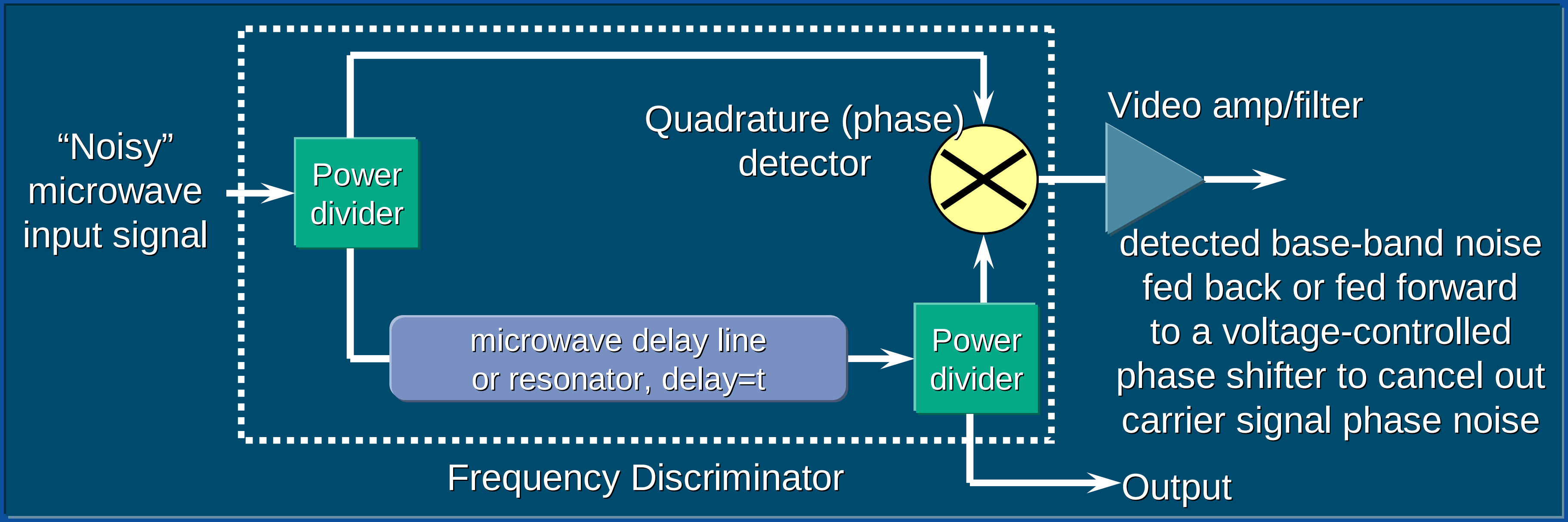
UHF VCO Phaselocked To HF Crystal Oscillator:

- 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



10. Oscillator Test and Troubleshooting Methods

Trouble Shooting Methods for: Discrete Transistor Sustaining Stage

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.

Trouble Shooting Methods for: Discrete Transistor Sustaining Stage

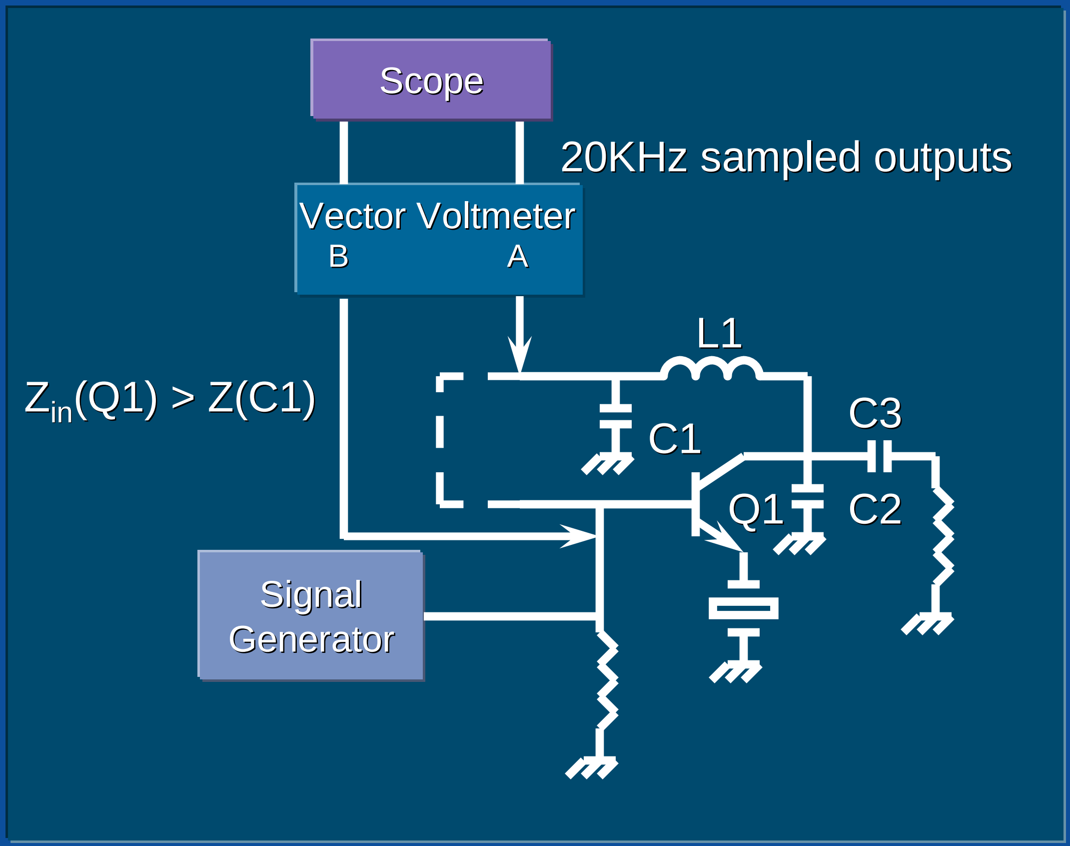
Steps, continued:

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



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.

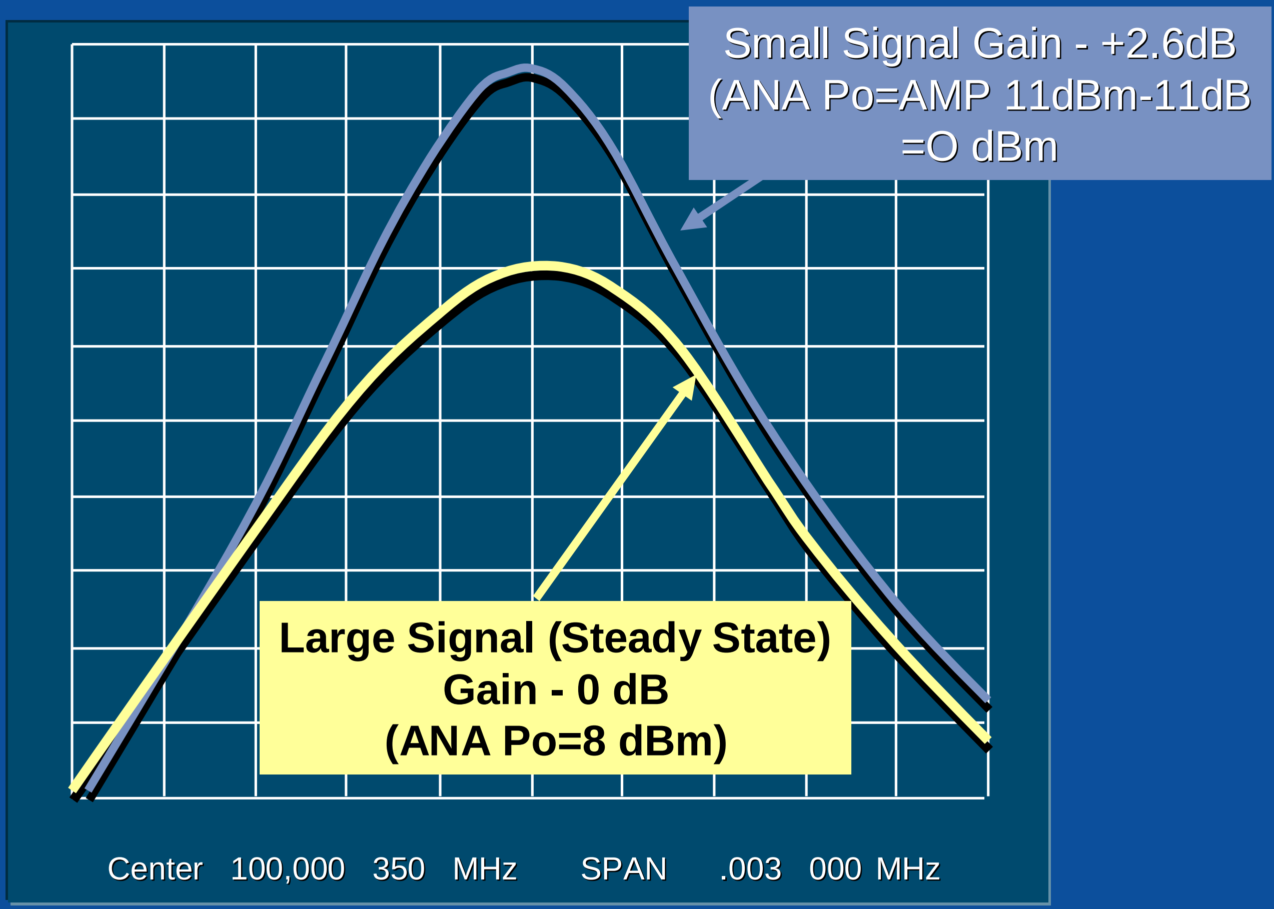
Modular Amplifier Sustaining Stage

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: s21 magnitude



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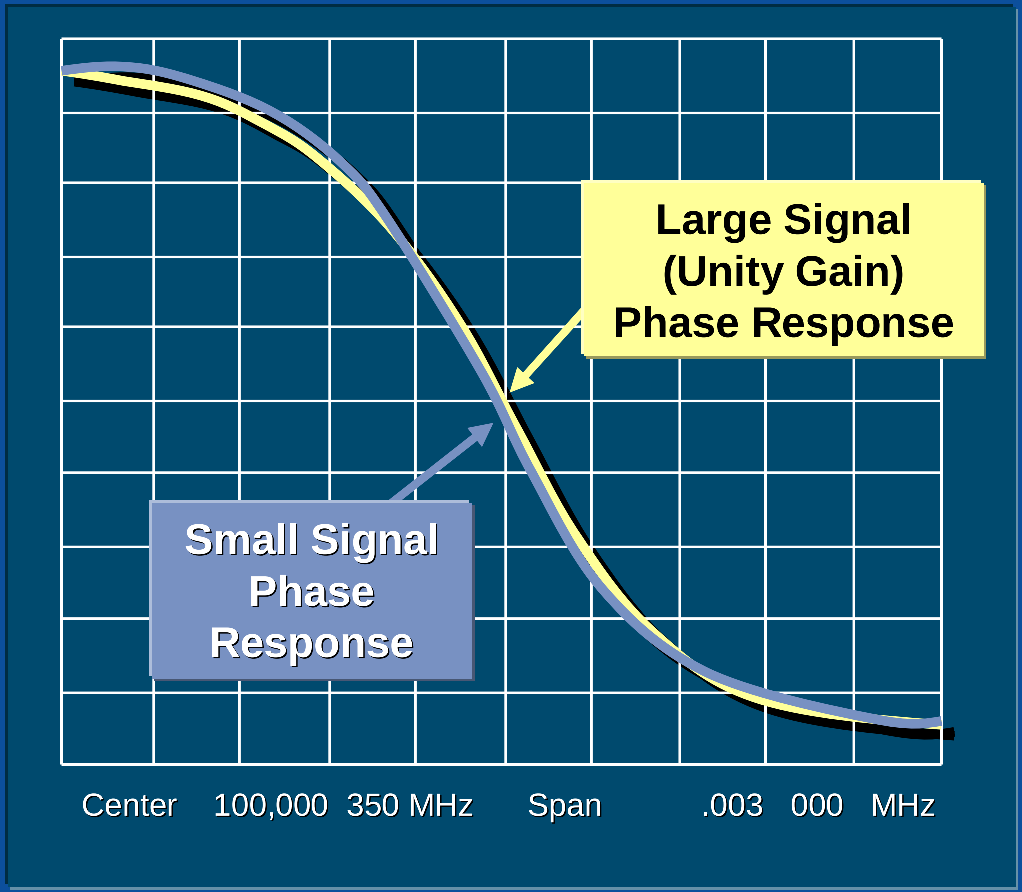
Typical Display of Network Analyzer Data

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



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

1-1. J. A. Barnes et. al., NBS Technical Note 394, "Characterization of Frequency Stability", U. S. Dept. of Commerce, National Bureau of Sta 1970.

1-2. D. Halford et. al., "Special Density Analysis: Frequency Domain Specification and Measurement of Signal Stability" Proc. 27th Freq. Contr. Symp., June 1973, pp. 421-431.

1-3. T. R. Faukner et. al., "Residual Phase Noise and AM Noise Measurements and Techniques", Hewlett-Packard Application Note, HP Part No. 03048-90011.

1-4. F. Labaar, Infrared and Millimeter Waves, Vol. 11, 1984.

1-5. D. W. Allan et. al., "Standard Terminology for Fundamental Frequency and Time Metrology", Proc. 42nd Freq. Contr. Symp., June 1988, pp. 419-425.

1-6. J. R. Vig, "Quartz Crystals Resonators and Oscillators: A Tutorial", U. S. Army Communications-Electronics Command Report SLCET-TR-88-1 (Rev. 8.5.1.6), December 2002, AD-M001251, http://www.ieee-uffc.org/index.asp?page=freqcontrol/fc_reference.html&Part=5#tutor.

1-7. W. F. Walls, "Cross-Correlation Phase Noise Measurements", Proc. 1992 IEEE Freq. Contr. Symp., May 1992, pp. 257-261.

1-8. M. M. Driscoll, "Low Noise Signal Generation Using Bulk Acoustic Wave Resonators:, Tutorial Session, 1993 IEEE Ultrason, Symp., Oct. 1993.

1-9. W. Walls, "Your Signal - a Tutorial Guide to Signal Characterization and Spectral Purity" Femtosecond Systems, Golden, CO, 1996.

1-10. Penny Technologies, Inc., "Correction Modules for Feed-forward Applications", Microwave Journal, Aug. 1996, pp. 142-144.

1-11. F. G. Ascarrunz, et. al., "PM Noise Generated by Noisy Components", Proc. 1998 IEEE Freq. Contr. Symp., June 1998, pp. 210-217.

1-12. M. M. Driscoll, "Evaluation of Passive Component Short-Term Stability via Use in Low Loop Delay Oscillators", Proc. 1999 EFTF-IEEE IFCS, April 1999, pp. 1146-1149.

1-13. D.A. Howe and T.K. Pepler, “Definitions of “Total” Estimators of Common Time Domain Variances”, Proc. 2001 IEEE Freq. Contr. Symp., June 2001, pp. 127-132.

2. Basic Oscillator Operation

2-1. D. B. Leeson, "A Simple Model of Feedback Oscillator Noise Spectrum", Proc. IEEE, Vol.54, No.2, Feb. 1966, pp. 329-330.

2-2. W. A. Edson, Vacuum Tube Oscillators, John Wiley and Sons, N.Y., 1953.

2-3. J. P. Buchanan, "Handbook of Piezoelectric Crystals for Radio Equipment Designers", Wright Air Development Center Tech, Report No. 56-156, Oct. 1956.

2-4. B. Parzen, The Design of Crystal and Other Harmonic Oscillators, John Wiley and Sons, N.Y., 1983.

2-5. E. A. Gerber et. al., Precision Frequency Control, Vol.2: Oscillators and Standards, Academic Press, Inc., 1985.

3. Types of Resonators and Delay Lines

3-1. J. P. Buchanan, "Handbook of Piezoelectric Crystals for Radio Equipment Designers", Wright Air Development Report No. 56-156, Oct. 1956.

3-2. D. Kajfez et. al., Dielectric Resonators, Aertech House, Norwood, MA.

3-3. E. A. Gerber et. al., Precision Frequency Control, Vol. 1: Acoustic Resonators and Filters, Academic Press, Inc., 1985.

3-4. A. J. Giles et. al., "A High Stability Microwave Oscillator Based on a Sapphire Loaded Superconducting Cavity", Proc. 43rd Freq. Contr. Symp., May 1989, pp. 89-93.

3-5. J. Dick et. al., "Measurement and Analysis of Microwave Oscillator Stabilized by Sapphire Dielectric Ring Resonator for Ultra-Low Noise", Proc. 43rd Freq. Contr. Symp., May 1989, pp. 107-114.

3-6. M. M. Driscoll, "Low Noise Microwave Signal Generation: Resonator/Oscillator Comparisons", Proc. 1989 IEEE MTT Digest, June 1989, pp. 261-264.

3-7. C. A. Harper, editor, Passive Component Handbook, Chapter 7: Filters, McGraw-Hill, Inc., N.Y., 1997.

3-8. M. J. Loboda, et. al., "Reduction of Close-to-Carrier Phase Noise in Surface Acoustic Wave Resonators", Proc. 1987 IEEE Ultrason, Symp., Oct. 1987, pp. 43-46.

3-9. S. Yao and L. Maleki, "Characteristics and Performance of a Novel Photonic Oscillator, Proc. 1995 IEEE Freq. Contr. Symp., June 1995, pp. 161-168.

3-10. M. S. Cavin and R. C. Almar, "An Oscillator Design Using Lowg-Sensitivity, Low phase Noise STW Devices", Proc. 1995 IEEE Freq.Contr. Symp., June 1995, pp. 476-485.

3-11. S. Yao, et. al., "Dual -Loop Opto-Electronic Oscillator", Proc. 1998 IEEE Freq. Contr. Symp., June 1998, pp. 545-549.

3-12. S. Yao, et. al., "Opto-Electronic Oscillator Incorporating Carrier Suppression Noise Reduction Technique", Proc. 1999 EFTF-IEEE IFCS Symp., April 1999, pp. 565-566.

3-13. T. McClelland, et. al., "100 MHz Crystal Oscillator with Extremely Low Phase Noise". Proc. 1999 EFTF-IEEE IFCS Symp., April 1999, pp.331-333.

3-14. M. M. Driscoll, "The Use of Multi-Pole Filters and Other Multiple Resonator Circuitry as Oscillator Frequency Stabilization Elements", Proc. 1996 IEEE Freq. Contr. Symp., June 1996, pp. 782-789.

4. Useful Network/Impedance Transformations

4-1. G. L. Matthaei et. al., Microwave Filters, Impedance Matching Networks, and Coupling Structures, McGraw-Hill, Inc., N.Y., 1964.

4-2. A. I. Zverev, handbook of Filter Synthesis, John Wiley and Sons, N.Y., 1967

5. Sustaining Stage Design and Performance

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

5-2. J. P. Buchanan, "Handbook of Piezoelectric Crystals for Radio Equipment Designers", Wright Air Development Center Tech. Report No. 56-156, Oct. 1956.

5-3. C. Halford et. al., "Flicker Noise of Phase in RF Amplifiers and Frequency Multiliers: Characterization, Cause, and Cure", Proc. 22nd Freq. Contr. Symp., April 1968, pp. 340-341.

5-4. M.M. Driscoll, "Two-Stage Self-Limiting Series Mode Type Crystal Oscillator Exhibiting Improved Short-Term Frequency Stability", Proc. 26th Freq. Contr. Symp., June 1972, pp. 43-49.

5-5. A. VanDerZiel, "Noise in Solid State Devices and Lasers", Proc. IEEE, Vol. 58, No.8, Aug. 1979, pp. 1178-1206.

5-6. B. Parzen, The Design of Crystal and Other Harmonic Oscillators, John Wiley and Sons, N.Y., 1983.

5-7. E. A. Gerber et al., Precision Frequency Control, Vol. 2: Oscillators and Standards, Academic Press, Inc., 1985.

5-8. M. M. Driscoll, "Low Noise Oscillators Using 50 - ohm Modular Amplifier Sustaining Stages", Proc. 40th Freq. Contr. Symp., May 1986, pp. 329-335.

5-9. G. K. Montress et. al., "Extremely Low Phase Noise SAW Resonator Oscillator Design and Performance", Proc. 1987 IEEE Ultras. Symp., Oct. 1987, pp. 47-52.

5-10. T. McClelland, et. al., "100 MHz Crystal Oscillator with Extremely Low Phase Noise", Proc. 1999 EFTF - IEEE IFCS Symp., April 1999. pp. 331-333.

6. Oscillator Frequency Adjustment/Voltage Tuning

6-1. M. M. Driscoll et. al., "Voltage-Controlled Crystal Oscillators", IEEE Trans. On Elect. Devices, Vol. Ed-18, No. 8, Aug. 1971, pp. 528-535.

6-2. R. Arekelian et. Al., "Linear Crystal Controlled FM Source for Mobile Radio Application", IEEE Trans. On Vehic. Tech., Vol. VT-27, No. 2, May 1978, pp. 43-50.

6.3. M. M. Driscoll, "Linear Tuning of SAW Resonators", Proc. 1989 IEEE Ultras, Symp., Oct. 1989, pp. 191-194.

7. Environmental Stress Effects

7.1 R. A. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review", IEEE Trans. UFFC, Vol. 35, No. 3, May 1988, pp. 297-305.

7-2. S. M. Sparagna, "L-Band Dielectric Resonator Oscillators with Low Vibration Sensitivity and Ultra-Low Noise", Proc. 43rd Freq. Contr. Symp., May 1989, pp. 94-106.

7-3. M. M. Driscoll, "Quartz Crystal Resonator G-Sensitivity Measurement Methods and Recent Results", IEEE Trans. UFFC, Vol. 37, pp. 386-392.

7-4. J. R. Vig, "Quartz Crystals Resonators and Oscillators: A Tutorial", U. S. Army Communications-Electronics Command Report SLCET-TR-88-1 (Rev. 8.5.1.6), December 2002, AD-M001251, http://www.ieee-uffc.org/index.asp?page=freqcontrol/fc_reference.html&Part=5#tutor.

7-5. M. M. Driscoll, "Reduction of Crystal Oscillator Flicker-of-Frequency and White Phase Noise (Floor) Levels and Acceleration Sensitivity via Use of Multiple Crystals", Proc. 1992 Freq. Contr. Symp., May 1992, pp. 334-339.

7-6. "Precision Time and Frequency Handbook", Ball Corp., Efratom Time and Frequency Products, 1993.

7-7. "IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators", IEEE STD 1193-1994.

7-8. J. T. Stewart et. al., "Semi-Analytical Finite Element Analysis of Acceleration-Induced Frequency Changes in SAW Resonators", Proc. 1995 Freq. Contr. Symp., May 1995, pp. 499-506.

NORTHROP GRUMMAN Electronic Systems

8. Oscillator Circuit Simulation and Noise Modeling

8-1. Super-Compact TM User Manual, Compact Software, Inc., Paterson, N. J.

8-2. M. M. Driscoll et. al., "VHF Film Resonator and Resonator-Controlled Oscillator Evaluation Using computer-Aided Design Techniques", Proc. 1984- IEEE Ultras. Symp., Nov. 1984, pp. 411-416.

8-3. M. Mourey, et. al., "A Phase Noise Model to Improve the Frequency Stability of Ultra-Stable Oscillator", Proc. 1997 IEEE Freq. Contr. Symp., June 1997, pp. 502- 508.

8-4. G. Curtis, "The Relationship Between Resonator and Oscillator Noise, and Resonator Noise Measurement Techniques", Proc. 41st Freq. Contr. Symp., may, 1987, pp. 420-428.

NORTHROP GRUMMAN Electronic Systems

9. Oscillator Noise De-correlation/Reduction Techniques

9-1. Penny Technologies, Inc., "correction Modules for Feed-forward applications", Microwave Journal, Aug. 1996, pp. 142-144.

9-2. F. L. Walls, et. al., "The Origin of 1/f PM and AM Noise in Bipolar Junction Transistors", Proc. 1995 IEEE Freq. Contr. Symp., May, 1995, pp. 294-304.

9-3. M. M. Driscoll, "Reduction of Quartz Crystal Oscillator Flicker-of-Frequency and White Phase Noise (Floor) Levels and Acceleration Sensitivity via Use of Multiple Resonators", Proc. 1992 IEEE Freq. Contr. Symp., May, 1992, pp. 334-339.

9-4. P. Stockwell, et. al., "Review of Feedback and Feed-forward Noise Reduction Techniques", Proc. 1998 IEEE Freq. Contr. Symp., May, 1998.

9-5. E. N. Ivanov, et. al., "Advanced Noise Suppression Technique for Next Generation of Ultra-Low Phase Noise Microwave Oscillators", Proc. 1995 IEEE Freq. Contr. Symp., May, 1995, pp. 314-320.

9-6. J. Dick et. al., "Measurement and Analysis of Microwave Oscillator Stabilized by a Sapphire Dielectric Ring Resonator for Ultra-Low Noise", proc. 43rd Freq. Contr. Symp., May 1989, pp. 107-114.

9-7 S. Yao, et. al., "Opto-Electronic Oscillator Incorporating Carrier Suppression Noise Reduction Technique", Proc. 1999 EFTF-IEEE IFCS Symp., April 1999, pp. 565-566.