# Phase Noise in Oscillators

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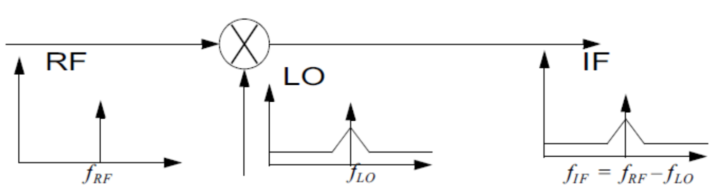
As well known from oscillator theory, two conditions are required to make a feedback system oscillate: the open loop gain must be greater than unity; and total phase shift must be 360° at the frequency of oscillation. The oscillations starts when Aβ >1 and returns to unity ( Aβ =1 ) once oscillations commence.

An oscillator circuit can be a combination of an amplifier with gain A (jω) and a frequency dependent feedback loop H (jω) = βA.
Oscillator has positive feedback loop at selected frequency.

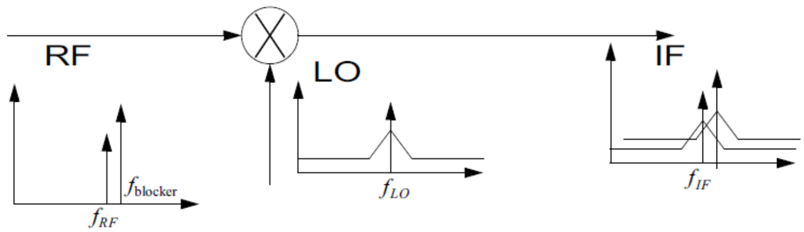
- Frequency Stability is a measure of the degree to which an oscillator maintains the same value of frequency over a given time.
- Phase Noise can be described as short-term random frequency fluctuations of a signal; is measured in the frequency domain, and is expressed as a ratio of signal power to noise power measured in a 1 Hz bandwidth at a given offset from the desired signal.
- Phase Noise is a measurement of uncertainty in phase of a signal. It is measured as the ratio of noise power in quadrature (90°out of phase) with the carrier signal to the power of carrier signal. This is opposed to AM noise which is noise in phase with the carrier signal.
- Two measurements of Phase Noise are common: the Spectral Density (SD) of phase fluctuations, and the Single Side Band (SSB) Phase Noise.
  Spectral Density is twice of SSB, since this is related to total phase change, which includes both sidebands, when SSB Phase Noise corresponds to the relative level on one sideband.

**The Phase Noise of a signal can only be measured by a system that has equal or better noise performance.**

- Low oscillator Phase Noise is a necessity for many receiving and transmitting systems. Adjacent Channel Rejection as well as transmitter signal purity are dependent on the Phase Noise of the receiver local oscillator or transmit local oscillator.
- The local oscillator Phase Noise will limit the ultimate Signal-to-Noise ratio (SNR) which can be achieved when listening to a frequency modulated (FM) or phase-modulated (PM) signal.
- In a heterodyne system, mixing a clean low-phase-noise RF signal, with a poor phase noise (noisy) local oscillator, it will turn into a noisy IF.



- The oscillator Phase Noise is transferred to the carrier to which the receiver is tuned and is then demodulated. The Phase Noise results in a constant noise power output from the demodulator.
- Reciprocal mixing is especially important in the presence of strong nearby interferers. The skirt from the down-converted interferer raises the noise floor for the down-converted signal well above Thermal Noise kTB.
- In a receiver, if a blocking interferer signal is much bigger than the desired signal, than the reciprocal Phase Noise due to the blocker self noise would dominate the noise at IF.

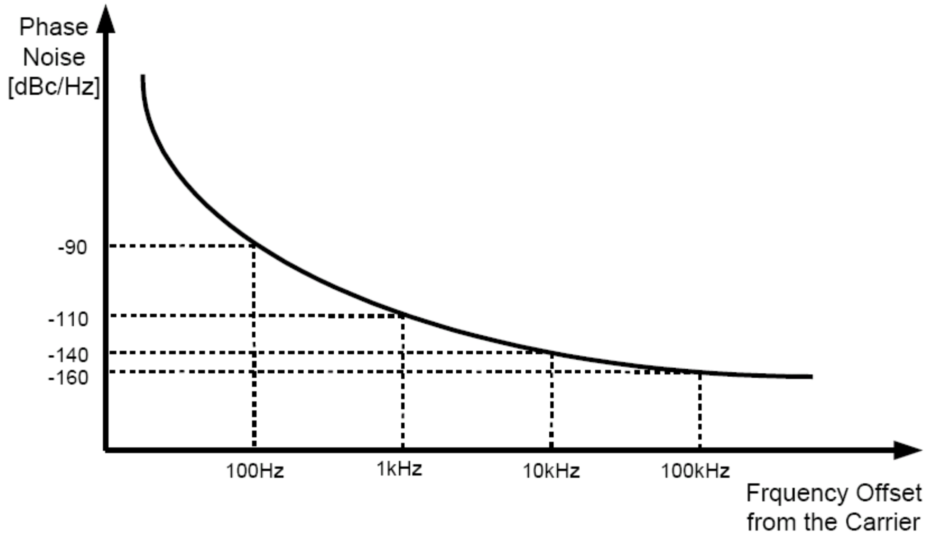



- The performance of some types of AM detectors or SSB detectors may be degraded by the local oscillator Phase Noise. Reciprocal mixing may cause the receiver noise floor to increase when strong signals are near the receiver's tuned frequency; this limits the ability to recover weak signals.
- Local oscillator Phase Noise will affect the Bit Error Rate (BER) performance of a Phase-Shift Keyed (PSK) digital transmission system. A transmission error will occur any time if the local oscillator phase, due to its noise, becomes sufficiently large that the digital phase detection makes an incorrect decision as to the transmission phase. For instance, a QPSK transmission system (used in Microwave Links, CDMA, DVB, etc) will make a transmission error if the instantaneous oscillator phase is offset by more than 45° since the phase detector will determine that baud to be in the incorrect quadrant. Digital transmission systems with smaller phase multiples are more sensitive to degradation due to local oscillator Phase Noise.
- Jitter is another factor that characterizes the oscillator signal and represents a fluctuation in the timing of the signal and arises due to the Phase Noise.
  Due to Jitter, the zero-crossing time of a periodic signal will vary slightly from the ideal location since the signal is not strictly periodic due to noise.

All of these effects are due to local oscillator Phase Noise, and can only be reduced by careful design decreasing the Phase Noise.

The Phase Noise of an oscillator is best described in the frequency domain where the spectral density is characterized by measuring the noise sidebands on either side of the output signal center frequency.

- Single Side Band (SSB) Phase Noise is specified in dBc/Hz at a given frequency offset from the carrier.

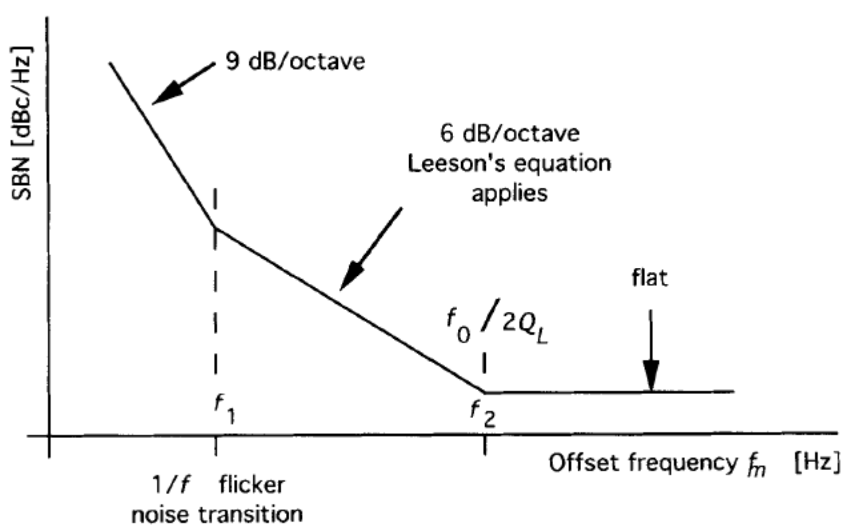



SSB Phase Noise places limit on receiver Adjacent Channel Selectivity (ACS) and also affects the receiver Signal to Noise Ratio.
A model for oscillator SSB Phase Noise was introduced by David B. Leeson in 1966.

$$\mathcal{L}_{PM} \approx 10 \log\left[\frac{FkT}{A}\frac{1}{8Q_L^2}\left(\frac{f_0}{f_m}\right)^2\right]$$ where:

$\mathcal{L}_{PM}$ = Single Side Band (SSB) Phase Noise density [dBc/Hz]
A = Oscillator output power [W]
F = device Noise Factor at operating power level A (linear)
k = Boltzmann's constant, 1.38 x $10^{-23}$ [J/K]
T = Temperature [K]
$Q_L$ = Loaded-Q [dimensionless]
$f_o$ = Oscillator carrier frequency [Hz]
$f_m$ = Frequency offset from the carrier [Hz]

Leeson equation only applies between 1/f flicker noise transition frequency ($f_1$) and a frequency ($f_2$) where white noise (flat) dominates.



Leeson equation provides several insights about oscillator SSB Phase noise:

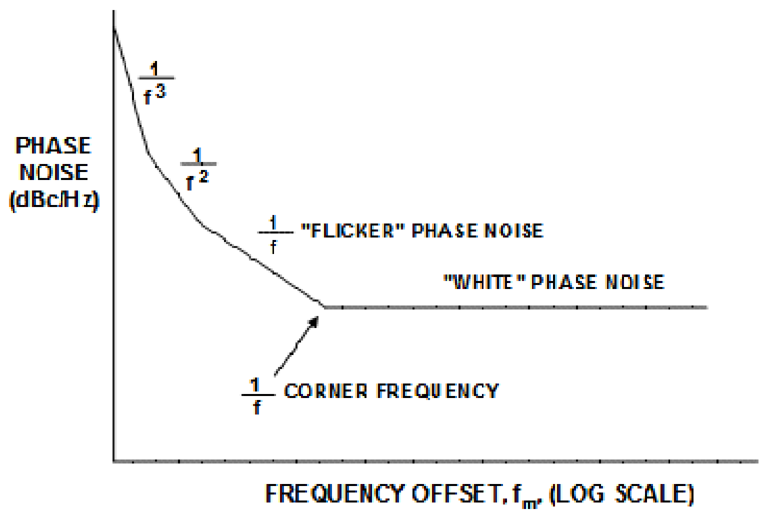
- Doubling the Loaded-Q improves Phase Noise by 6dB.
- Doubling the operation frequency results 6dB Phase Noise degradation.

**Unloaded-Q** means the resonant circuit is not loaded by any external terminating impedance. In this case the Q is determined only by resonator losses.
**Loaded-Q** represents the width of the resonance curve, or phase slope, including the effects of external components. In this case the Q is determined mostly by the external components.

- It is a common design mistake to achieve high Loaded-Q values by using a very loosely coupled resonator. The under-coupling results in increased overall resonator loss requiring an extra amount of gain to compensate it, which in turn, results in thermal noise increase.
- Resonator loss is a function of its unloaded and loaded Q-factors and is given by:

$$L(dB) = 10\log\left(\frac{1}{1-\frac{Q_L}{Q_U}}\right)^2$$

For example, in a simple feedback oscillator, the minimum Phase Noise is achieved when the resonator Loaded-Q is set to one half of its Unloaded value ($Q_L = 0.5*Q_U$) that corresponds to a 6dB resonator loss.
Other oscillator schemes may require different optimum coupling values due to different design goals and trade-offs.




- In the figure above Phase Noise in dBc/Hz is plotted as a function of frequency offset ($f_m$), with the frequency axis on a log scale. Note that the actual curve is approximated by a number of regions, each having a slope of $1/f^x$, where x = 0 corresponds to the "white" phase noise region (slope = 0 dB/decade), and x = 1 corresponds to the "flicker 1/f" phase noise region (slope = 20 dB/decade). There are also regions where x = 2, 3, 4, and these regions occur progressively closer to the carrier frequency.

- Leeson equation assumed that the $1/f^3$ and $1/f^2$ corner occurred precisely at the 1/f corner of the device. In measurements, this is not always the case.
- The Phase Noise of an oscillator depends by the noise of the open-loop amplifier and by the half-bandwidth of the resonator. If the amplifier has no 1/f noise region, the oscillator will have $1/f^2$ noise below the half-bandwidth. Unfortunately, all the active devices have some sort 1/f region.
- If the 1/f "flicker" corner frequency is low, the oscillator will have $1/f^2$ noise slope until that corner frequency is reached. This is the case with many LC oscillators.
- The 1/f region might be due to either active device or resonator. In many cases the noise of the resonator dominates, especially in the case of crystals or SAW devices. In this situation, the crystal should be presented with impedance that doesn't degrade the Q, or else the Phase Noise will also be degraded.

**Oscillator harmonics can be filtered out by a simple Low Pass Filter, when the spurious close to the carrier can only be minimized by careful oscillator design.**

**Rules for designing a low Phase Noise oscillator:**

- Maximize the resonator Loaded-Q. To do this (but trading with gain), in the series resonant circuits use a large Inductor, and in parallel circuits use a large Capacitor. Coupling the resonator tightly to the oscillating device, and minimize the coupling of the load to the circuit.
- A 10dB increase in Loaded-Q results in a 20dB improvement in Phase Noise.
- Build the resonator using high-Q components, having constant and quiet noise.
- Low losses are required in all of the constituent parts of the circuit including PCB. To be carefully considered the series resistance of the reactive components. Coupled losses in the rest of the circuit should be at most equal to the resonator losses. To get best Phase Noise, the resonator losses should be x3 the circuit losses.
- Use an active device with low noise figure at low frequencies.
- Use an active device with low 1/f flicker noise, with good bias circuit. The DC current set to get the best 1/f flicker noise should be the oscillator device current.
- There is effectively a trade-off between Gain and Phase Noise performance in microwave transistors, both for the additive or multiplicative noises.
- Maximize the output Signal Power vs Noise Power of the oscillator.
  However, the output power increase should be implemented very carefully, since severe Phase Noise degradation can occur because of the active device noise elevation at compression.
- Extract the output signal through the resonator to the load, thereby using the resonator transmission response selectivity to filter the carrier noise spectrum.
- Optimize (and do trade-offs) in noise reduction where is needed, especially consider close-in noise vs large offset noise requirements.
- Power Supply ($V_{CC}$) and tuning voltage ($V_{tune}$) returns must be connected to the printed circuit board ground plane. VCO ground plane must be the same as that of

the printed circuit board and therefore all VCO ground pins must be soldered direct to the printed circuit board ground plane.

- Adequate RF grounding is required. Several chip decoupling capacitors must be provided between the $V_{CC}$ supply and ground.
- Good, low noise power supplies must be used to prevent AM noise. Ideally, DC batteries for both supply ($V_{CC}$) and tuning ($V_{tune}$) voltages will provide the best overall performance.
- The biasing circuit of the active device should be properly regulated and filtered to avoid any unwanted signal modulation ore noise injection. Variations on the supply voltages or currents may also cause undesirable output power fluctuations and frequency drift.
- The active device should work in Class-A, to minimize the limitations in the stage that drives the resonator.
- Carefully control the limiting amplitude mechanism, so as not introduce AM noise. A signal limiter can be placed either before or after the active device, keeping its output well below the compression level.
- AM-PM conversion is minimized by choosing a 90° crossing angle between the device line and the load line.
- Phase perturbation can be minimized by using high impedance devices such as FETs, where the Signal-to-Noise ratio of the signal voltage relative to the equivalent noise voltage can be made very high.
- Output must be correctly terminated with good load impedance. It is also a good practice to use a resistive pad between the VCO and the external load.
- Connections to the tuning port must be as short as possible and must be well screened, shielded, and decoupled to prevent the VCO from being modulated by external noise sources. A low noise power supply must be used for tuning voltage.
- Minimize Frequency Pushing by the Gate or Base voltage of the transistor. Frequency Pushing is a shift in the oscillation frequency usually caused by a change in the transistor bias voltage.
- Avoid saturation of the active devices at all cost, and try to have either limiting or automatic gain control (AGC) without degradation of the Q of the resonator. Saturation of the active device can also lower the loaded-Q since the device losses will then add to those of the resonator.
- Use active components with low 1/f-noise. Flicker noise in active devices is also known as 1/f noise because of the 1/f slope characteristics of the noise spectrum (the amplitude varies inversely with frequency). Mainly traps associated with contamination and crystal defects in the emitter-base depletion layer cause this noise (in BJTs case). These traps capture and release carriers in a random fashion. The time constant associated with the process produce a noise signal at low frequencies.
- Transistors made in different processes have different 1/f noise corners. JFETs are the best (~1kHz), followed by BJTs (~5kHz), then CMOS (~1MHz), and GaAs are the worst (~10MHz).
- Consider using noise reduction via feedback, or feed-forward noise reduction techniques.

## Rules for designing a low Phase Noise Voltage Controlled Oscillator (VCO):

In a Phase-Locked Loop (PLL) a Voltage Controlled Oscillator (VCO) will always have some spurious signals present on its output.
The amplitude and frequency of these spurious modulations may vary as the local oscillator is tuned.

- Poor layout of the phase-locked loop oscillator circuitry (VCO) may increase the amplitude and number of the output spurious signals.
- Oscillator Phase Noise has two components: Phase Noise resulting from direct upconversion of white noise and flicker noise (1/f noise), and Phase Noise resulting from the changing phase of the noise sources modulating the oscillation frequency.
- In VCO design another source of Phase Noise increase are the non-linear capacitors (varactors) used in the LC resonator and its control lines.
- In a VCO, have to maintain the Q of the resonator by avoiding forward bias on the varactor tuning diodes, limiting the signal swing across the tuning diodes to prevent heating and thermal effects. This can be achieved by placing the varactor circuit in the gate or base if possible.
- Two back-to-back varactors should be used to avoid self-rectification of the RF signal across the varactors, which always results in phase noise degradation.
- The noise from the varactor diode resistance can also become the dominant noise source. For good Phase Noise, the carrier signal effectively appearing across the varactor noise resistance should be maximized to maintain good Signal-to-Noise ratio at this point. By transforming the noise load resistance seen by the oscillating device to a lower value in the matching circuit, the Power-to-Noise ratio across the varactor can be maximized, although at the expense of tuning bandwidth since the matching circuit will restrict the obtainable capacitance variation.
- There is a compromise in order to avoid breakdown, saturation, or overheating effects in the varactor. These will all reduce the Loaded-Q.
- When frequency of the carrier increases, it is more difficult to achieve good Phase Noise
- It’s easy to achieve good Phase Noise when the frequency range covered by VCO is narrow; the tuning bandwidth must be small. Generated energy should be coupled from the resonator rather than from another portion of the active device so that the resonator limits the bandwidth.
- Increasing tuning sensitivity (measured in MHz / V) degrades Phase Noise.
- For a given frequency it’s easy to achieve good Phase Noise in VCO’s using a wide tuning voltage range.
- Temperature affects the Phase Noise. In a range of –55’C to +85’C the variation is +/- 3dB of the Phase Noise.
- Using of back-to-back varactor diodes in the tuning circuits has been found to eliminate effects of tuning circuit diode noise on oscillator signal spectral performance.

## Characteristics of the ideal resonator for low Phase Noise oscillator:

- 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.
- 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.

Passive 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.

## Rules to select a transistor and its bias for designing a low Phase Noise oscillator:

- The best oscillator transistor is a device with the lowest possible noise figure and lowest $f_T$. A commonly used criteria is: $f_T \leq 2 * f_{osc}$.
- Meantime, doing a trade-off, have to use a high frequency transistor having small junction capacitance and operate at moderately high bias voltage to reduce phase modulation due to junction capacitance noise modulation.
- Low 1/f noise of the transistor in the oscillator is very important, because the 1/f noise appears as sideband noise around the carrier frequency of the oscillator output signal.
- The 1/f noise is directly related to the current density in the transistor. Transistors with high $Ic_{max}$ used at low currents have best 1/f performance. For low Phase Noise operation use a medium power transistor. If you need your output power to be achieved at 6-9 mA, select a transistor with $Ic_{max}$ of 60-90 mA. However, the $f_t$ of a transistor drops as current is decreased. Additionally, the parasitic capacitances of a high current transistor are higher due to the larger transistor structure required.

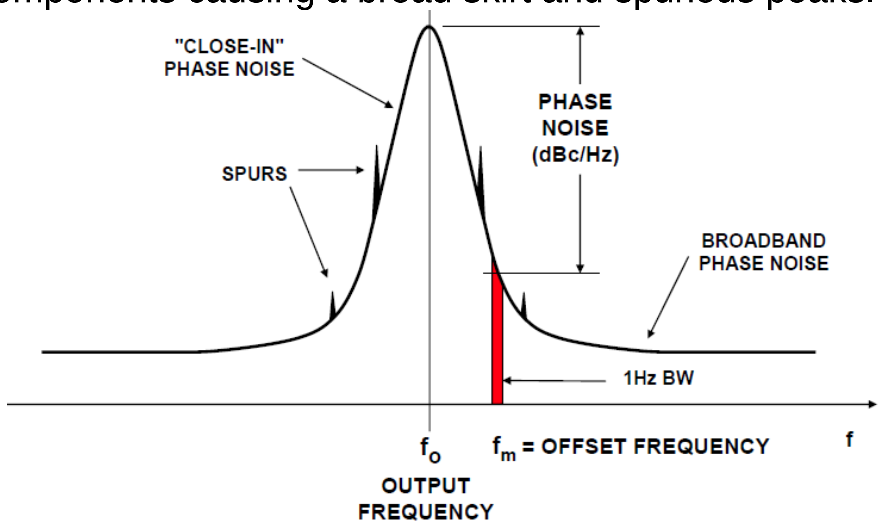
- In BJTs as $V_{CE}$ increases, the flicker corner increases as the white noise increases, but the magnitude of the 1/f noise is constant. As base current increases, the flicker corner frequency increases with the magnitude of the 1/f noise and the increased shot noise current.
- The effect of flicker noise can be reduced through RF feedback. An unbypassed emitter resistor of 10-30 Ω in a BJT circuit can improve the flicker noise by as much as 40 dB. The proper bias point of the active device is important.
- In a well-designed near-class-A oscillator, the frequency is determined primarily by the resonator. As the loaded-Q is increased, the active device parasitic reactances become less significant in determining the oscillation frequency.
  Thus, changes in these parameters from device to device, with temperature and with supply voltage, have less effect. A simple test of how well the active device reactances are isolated from the resonator is to observe the operating frequency as the supply voltage is varied.
- Precautions should be taken to prevent modulation of the input and output dynamic capacitances of the transistor; which will cause amplitude-to-phase conversion and therefore introduce noise.
  If phase shift in the transistor changes, the oscillation frequency will change until the loop phase shift returns to zero. Thus, phase modulation in the amplifier causes frequency modulation of the oscillator.
- Device with low noise figure combined with a small correlation coefficient.
- Device with relative high output power.
- Device with low output conductance.
- Device with reasonably high input impedance.
- Meeting an impedance condition at the input of the active device, which can be achieved by optimization of the feedback factor and which leads to optimum impedance noise matching.
- Device with low multiplicative noise (1/f AM and especially 1/f PM).
- Device having 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.
- Device with low Group Delay (wide bandwidth).
- Device with high load circuit isolation.
- Device with minimal number of adjustable and bias components.
- Ease of alignment and test.
- Device with good DC efficiency.

## Phase Noise in PLL (Phase Lock Loop) oscillators

A Phase Lock Loop (PLL) is a type of a controlled oscillator where the frequency stability is of critical importance. PLL designers are interested in both, long-term frequency stability (over a long period of time, hours, days, or months) and short-term stability (over a period of seconds or less).

Frequency stability it is usually specified as the ratio, Δf/f for a given period of time, expressed as a percentage or in dB. These frequency variations can be random or periodic.

- A spectrum analyzer can be used to examine the short-term stability of a signal, as in the figure below where is shown a typical spectrum, with random and discrete frequency components causing a broad skirt and spurious peaks.

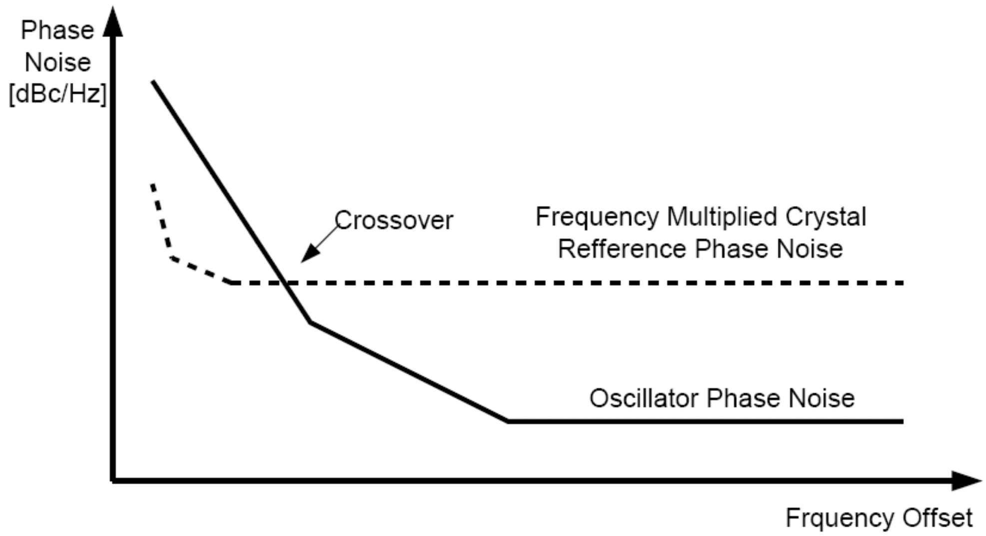



- The discrete spurious components could be caused by known clock frequencies in the signal source, power line interference, and mixer products.
- The broadening caused by random noise fluctuation is due to phase noise.
  It can be the result of thermal noise, shot noise, and/or flicker noise (1/f noise) in active and passive devices.
- The phase noise spectrum of an oscillator shows the noise power in a 1 Hz bandwidth as a function of frequency.
  Phase noise is defined as the ratio of the noise in a 1 Hz bandwidth at a specified frequency offset, $\mathbf{f_m}$, to the oscillator signal amplitude at frequency $\mathbf{f_o}$.

**In a PLL the design of the loop filter can affect the Phase Noise of the system:**

- Within the loop bandwidth, the Phase Noise of the oscillator will tend to cancel itself, leaving a Phase Noise essentially equal to the frequency multiplied Phase Noise of the crystal reference.
- Multiplied Phase Noise of the crystal reference at particular frequency offset is equal with reference Phase Noise at the same frequency offset plus 20*LOG($N_{VCO\_divider}$) plus 1dB (multiplication efficiency factor).
- Outside the loop bandwidth, the Phase Noise of the oscillator is not canceled, and will continue to decrease, until reaching its half bandwidth, $\omega_o/2Q$ or 1/f corner frequency.
  Since the Q of the crystal reference is very large, its half bandwidth is very small, and its frequency multiplied Phase Noise will remain relatively flat down to very small frequency offsets. Further, at some moderate frequency offset, this multiplied phase noise power spectral-density will be crossed by the decreasing oscillator phase noise power spectral-density.

- The bandwidth of the loop should be chosen equal to the frequency offset of this crossover.



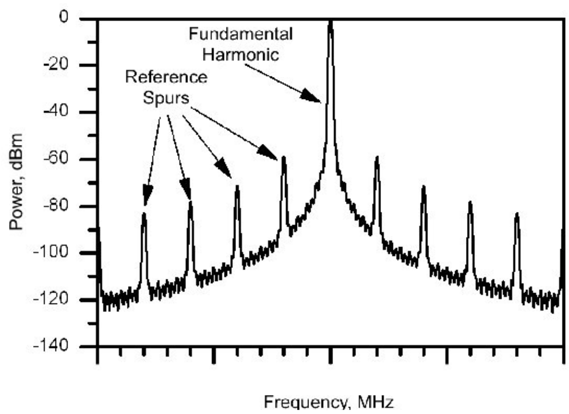

- Typically, crystal-based oscillators have good phase noise performance close to the carrier frequency and the VCO of this PLL offers a low noise floor (>1 MHz from the carrier). The PLL loop bandwidth should be set in such a way that the output phase noise can take advantage of the low phase noise of reference clock at close to carrier frequency and the low phase noise floor of the VCO. The in-band phase noise of the PLL contributes up to the loop bandwidth frequency.
- To minimize the output noise due to the VCO, the loop bandwidth must be as large as possible.
- To achieve minimum phase noise within the loop bandwidth, the in-band noise contributed by the other loop components should be kept to a minimum.
- The loop bandwidth must be less than the input reference frequency to keep the loop stable and suppress the spurs at the output due to the reference leakage signal.
- The PLL loop bandwidth is not a barrier frequency with a discontinuity on either side of the barrier; it can be approximated as such with the proviso that small errors around the offset frequency equal to the loop bandwidth are accepted.
- The role of the loop filter, which is a low-pass filter inserted between the phase comparator and the VCO control voltage circuit, eliminates the high frequency component of the phase correction pulse generated by the phase comparator so that the only the DC component is provided to the VCO.
- As a rule of thumb, the cut off frequency of the low-pass filter is chosen as equal or less than comparison frequency divided by ten; $F_{cutooff} < (F_{comparision} / 10)$
- Usually the low-pass filter is an RC network. The analysis of the Phase Noise performance shows that the Phase Noise depends on the resistor value, part of the low-pass filter. The higher the resistor, the higher is its contribution to the Phase Noise.

- The noise spectrum of a frequency source is made up of (at least) five components:

1. Random frequency walk
2. Flicker frequency noise
3. Random phase walk (white FM)
4. Flicker phase noise
5. White phase noise

These components each dominate within a particular region of the phase noise spectrum, and the conversions are a piecewise linear approximation to the spectrum.
Each component is converted separately. Therefore, it may well be quicker and more accurate to make the measurement in question than to convert from one to the other.

In the figure below is shown a spectrum analyzer presentation of the output of a typical phase lock frequency synthesizer.



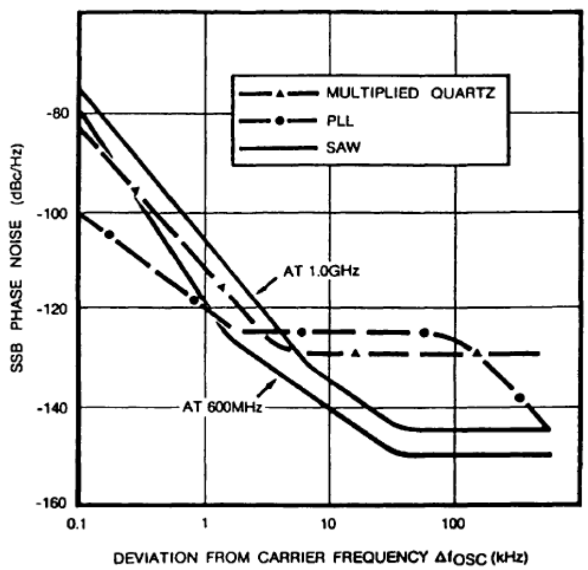
PLL reference spurs shown on a spectrum analyzer

The spurs, which could be down about 40dB to 80dB, are at the reference frequency and its harmonics, and are the most difficult to suppress unwanted output from a phase lock synthesizer. They are produced by undesired frequency modulation of the VCO by the reference frequency output of the phase detector, which should ideally be rejected by the loop filter.

- When considering oscillator phase noise, we assume a signal such as that from a local oscillator, and consider that the noise is made up of two components in quadrature, one of which is an **amplitude noise component** and the second a **phase noise component**.
- However, because it is regenerative, the action of an oscillator is such that its output amplitude continues to build up until it cannot increase any more.
  This means that an oscillator's output normally suppresses amplitude noise, although it can appear as AM-to-PM noise but at a greatly reduced level.
- The higher the Q of the resonator, the lower is the effect of AM-to-PM noise conversion, as well as the phase noise itself. The overall result is that there is very little AM noise to start with, and what little there is, is converted to phase noise.
  The best approach to phase noise reduction is to increase the Q of the resonator in the signal source.

- There are three different means of generating high-frequency signals, and each of them produce different single-sideband (SSB) spectrum.

  1. **Direct multiplication** of a quartz crystal-stabilized oscillator, generating a low- frequency signal, to a high frequency.
  2. Use of a **phase lock loop synthesizer** to multiply a low crystal frequency reference signal to a high frequency.
  3. Use of a high-frequency **surface acoustic wave resonator** in an oscillator to generate a high-frequency signal directly.




Comparison of SSB phase noise of three techniques for high-frequency local oscillator signal generation

- The test results carried out to compare the single-sideband phase noise at offsets of more than approximately 8 kHz, shows that the direct, surface acoustic wave oscillator approach has the lowest phase noise.
- Below 1 kHz offset, however, the phase lock technique is lowest in phase noise.

## Phase Noise in Crystal Oscillators

One of the most important characteristics of crystal oscillators, besides they can provide good frequency stability, is that they can exhibit very low Phase Noise.

In many oscillators, any spectral energy at the resonant frequency will be amplified by the oscillator, resulting in a collection of tones at different phases.

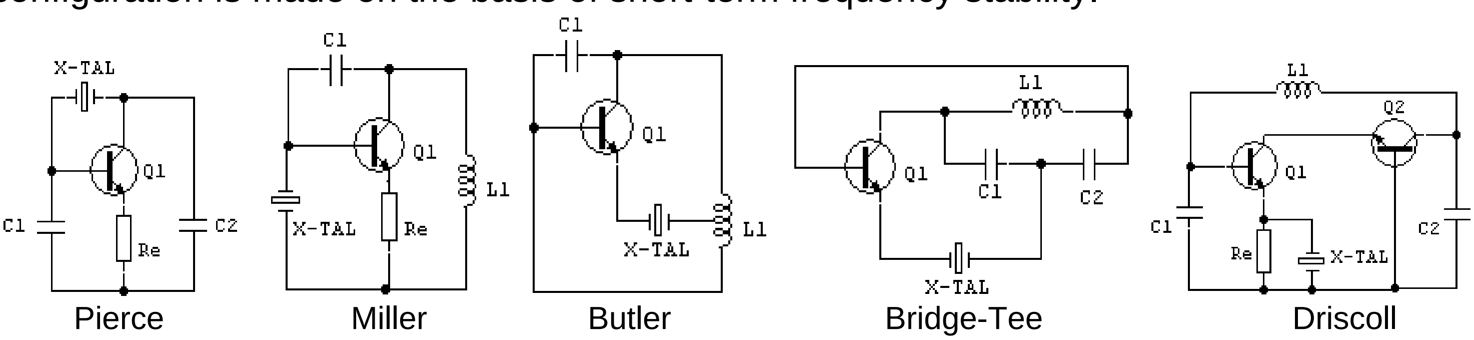
In a crystal oscillator, the crystal mostly vibrates in one axis, therefore only one phase is dominant.

- At lower offset frequencies approaching the carrier, the Phase Noise is determined by the quality Q of the crystal resonator. For example a 100MHz crystal has a considerably lower Q than a 10MHz crystal, so the noise is higher at the low offsets.

The amplitude of **1/f flicker noise in crystal resonators** is a very important parameter of oscillators used in various applications.

- To get accurate models of the 1/f frequency noise in the resonator itself, this should be independent of the noise generated by the afferent electronic circuit.
- Was discovered that the amplitude of the 1/f frequency noise in a crystal depends not only on the Q of the resonator but also on the volume between the electrodes. Since the amplitude of 1/f noise depends on active crystal volume, to get low close-in Phase Noise we have to use the lowest overtone and lowest resonator frequency.
- Extra noise source is associated with electrode-crystal interface.
  A resonator having smaller electrodes would have lower 1/f flicker noise than other with the same resonant frequency and Q, but with larger diameter electrodes.
- The decrease in electrode area would increase the impedance and degrade the wideband noise, but for most resonators the wideband noise is dominated by the electronics of the oscillator.
  The increase in series resistance decreasing the electrode diameter by a factor of 4 would be probably the limit from the standpoint of wideband noise.
  This change might lead in a change of the oscillator loop gain.
- Thus, for application specifically requires minimum close-in Phase Noise, lower frequency crystals may be used, when for low noise floor applications (wideband noise), the highest frequency crystal which satisfies long term stability requirements should generally be used.
- Also was discovered that 1/f frequency noise in a crystal is virtually independent of the loaded-Q of the resonator, when we know that in a practical oscillator circuit there is a dependence of the Phase Noise on loaded-Q, because the sustaining electronics contribute to the overall noise level.
- The crystal resonator plate can be cut from the source crystal in many different ways. The orientation of the crystal cut influences the crystal's frequency stability, Phase Noise characteristics, aging characteristics, thermal characteristics, and other parameters. A special cut (SC - Stress Compensated), is a double-rotated cut developed for oven stabilized oscillators with low Phase Noise, and good aging characteristics. This special cut SC is less sensitive to mechanical stresses, and has faster warm-up speed, higher Q, better close-in Phase Noise, less sensitivity to spatial orientation, and less sensitivity to vibrations.

Various topologies of crystal oscillators exhibit different performances mainly due to the limiting functions of the circuit, and of the loaded-Q of the crystal resonator.
In many instance decisions of selection of particular type of crystal oscillator configuration is made on the basis of short-term frequency stability.




Crystal Oscillator Topologies

In most anti-resonant circuit configurations (such as Pierce and Miller configurations), the out-of-band impedances may become reactive due to the sharp reactance vs frequency characteristic exhibited by the crystal unit.

The series-mode circuits (as Butler and Bridge-Tee configurations) are more effective in reducing the wideband noise floor (up to 10dB compared to anti-resonant circuit).

The main disadvantage of series-mode circuits is the large degradation in crystal unit loaded-Q (due to limiting of the transistor). For example, the effective value for crystal unit loaded-Q is about 120.000 for the Pierce circuit, and 24.000 for Bridge-Tee circuit.

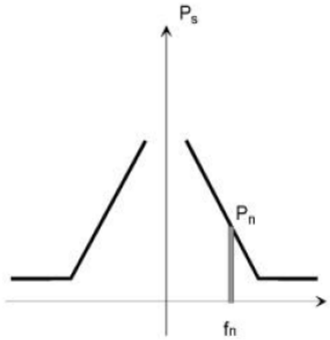
- When limiting occurs, the transistor is turned OFF for a time portion of the signal waveform, time when the impedance seen by the crystal resonator at the transistor emitter contains a large value component at the signal frequency. This component of transistor impedance (which becomes increasingly large as the excess gain in the sustaining stage is increased) it will degrade the oscillator loaded-Q.
- In addition, the degradation in crystal loaded-Q can produce degradation in oscillator long-term frequency stability. This includes changes caused by environment (temperature, humidity) long-term power supply variation, and short-term effects (vibration and power supply ripple).
- Thus, better output noise spectrum could be obtained using a crystal oscillator in series-mode configuration, employing class-A non-limiting action in the sustaining stage transistor.
- The limiting function in a crystal oscillator may be controlled by:
  1. Auxiliary low-noise AGC circuits (a portion of the amplified RF signal is rectified and used to control the RF gain of the sustaining stage).
  2. Back-to-back Schottky diodes incorporated in the oscillator circuit, so that the diode RF impedance presented to the sustaining stage (and hence the RF gain) decreases with increasing the RF level.
  3. Incorporation of a second self-limiting transistor stage in the oscillator sustaining circuit, in a manner such that its effect on crystal unit loading is insignificant.

In 1972 M.M. Driscoll developed a very low Phase Noise series-mode crystal oscillator employing two transistors connected in cascode configuration.

- The quartz crystal resonator is used as an un-bypassed emitter load on Q1.
- Unlike the common Butler or Bridged-Tee circuits, Q1 is ON during the full cycle of the signal waveform, since the limiting function is provided in Q2.
- Connecting the crystal between emitter of Q1 and ground increase the crystal loaded-Q. Reducing the emitter impedance by increasing the bias current of Q1 avoid over-dissipating power into the crystal.

## Measuring the Oscillator Phase Noise

Generally, the Spectral Density, or Phase Noise, of an oscillator is measured in dBc (dB below the carrier) in a bandwidth of 1Hz at an offset frequency $f_n$.
The Phase Noise, therefore, is related to the output power.
The Noise Power and the curve can have different shapes based on the noise sources.




**Phase_Noise$_{[dBc/Hz]}$ = 10*LOG ($P_n$ / $P_s$)**

$P_n$ = Noise Power in 1Hz Bandwidth at particular frequency offset ($f_n$) in Watts
$P_s$ = Carrier signal power in Watts

**A.** The simplest and fastest method of determining the Phase Noise of an oscillator is the direct measurement using a Spectrum Analyzer.

For this measurement, the tested oscillator must fulfill the following conditions:

- The oscillator drift must be small relative to the Spectrum Analyzer sweep time since otherwise the oscillator frequency varies during the sweep, leading to distorted results. The synthesizers commonly used in radio communications fulfill this condition since they are locked to a stable reference.
- The Phase Noise of the local oscillators of the Spectrum Analyzer must be low enough to ensure that the characteristics of the tested oscillator and not those of the Spectrum Analyzer are determined.

Factors that limit the analyzer's ability to correctly measure the Phase Noise of a signal:

- IF (RBW) filter bandwidth, verses noise bandwidth.
- IF filter type and shape factor.
- Analyzer's local oscillator stability - residual FM.
- Analyzer's local oscillator stability - noise sidebands.
- Analyzer's detector response to noise - peak detector introduces errors.
- Analyzer's log amplifiers response to noise.
- Noise floor of the analyzer.

When measure the oscillator Phase Noise using a Spectrum Analyzer the following equation can be used for direct reading in dBc/Hz, for particular Resolution Bandwidth (RBW) set on the analyzer:

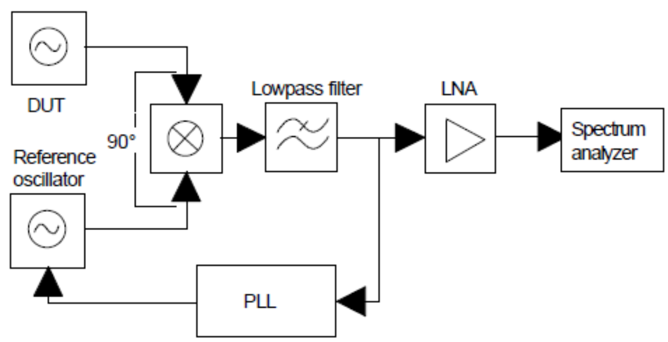
**Phase_Noise$_{[dBc/Hz]}$ = Carrier_Power$_{[dBm]}$ – Noise_Power@Freq_offset$_{[dBm]}$ – 10*LOG (RBW$_{[Hz]}$)**

Spectrum Analyzers generally only measure the scalar magnitude of noise sidebands of the signal and are not able to differentiate between amplitude noise and phase noise.
In addition, the measurement process is complicated by having to make a noise measurement at each frequency offset of interest, sometimes a very time consuming task.

**B.** Another Phase Noise measurement can be done using a Reference Oscillator and a Phase Detector:

- The Phase Detector converts phase difference between its two inputs into a voltage When the phase difference between the two inputs is 90° (quadrature) the Phase Detector output will be 0 volts.
- Any phase fluctuations around the quadrature point will result in a voltage fluctuation at the output of the Phase Detector.
- The Phase Detector output can then be digitized and processed to obtain the phase noise information desired.
- Additionally, the Phase Detector technique also enables residual/additive noise measurements for two-port devices.

Several methods have been developed based upon the phase detector concept. Among them, the Reference Source / PLL (Phase Locked Loop) is one of the most widely used methods.



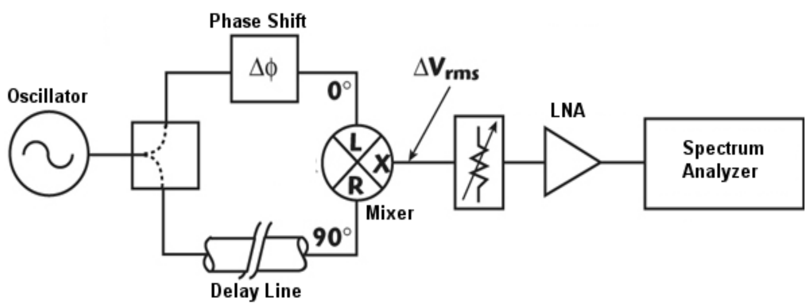

Phase Noise measurement using a Reference Oscillator and a Phase Detector

- The reference oscillator is synchronized to the measured oscillator by means of a PLL of a very small bandwidth.
- The PLL sets the phases of the two oscillators to a difference of 90°.
- The Phase Noise of the DUT is eliminated within the loop bandwidth.
- The sum noise power of the reference and the test oscillator obtained outside the loop bandwidth is present at the output of the phase detector.
- This output signal is amplified by means of an LNA (Low Noise Amplifier) and displayed on a Spectrum Analyzer starting at a frequency of 0Hz.

This method offers the advantage of a very wide dynamic range, provided that the reference oscillator is of a very high spectral purity. Often, two identical oscillators are used for measurements on crystal oscillators, and the assumption made that the two oscillators have the same Phase Noise. In this case, 3 dB is subtracted from the result because the noise powers add up.
Also, this method yields the widest measurement coverage (e.g. the frequency offset range is 0.01 Hz to 100 MHz).
This method is insensitive to AM noise and capable of tacking drifting sources.

The disadvantages of this method are:
- The method requires two oscillators at the same frequency that have to be synchronized to each other.
- An extra PLL and a Low Noise Amplifier are needed.
- Calibration is complex because the gain of all components is included in the result. Calibration is made by mistuning the two oscillators relative to each other and measuring the AC voltage obtained at the output of the LNA.
- Requiring a clean, electronically tunable reference source, and that measuring high drift rate sources requires reference with a wide tuning range.

**C.** The Frequency Discriminator method is another variation of the Phase Detector technique with the requirement of a reference source being eliminated.




- The signal from the tested oscillator is split into two channels.
- The signal in one path is delayed relative to the signal in the other path.
- The delay line converts the frequency fluctuations to phase fluctuations.
- Adjusting the delay line or the phase shifter will determine the phase quadrature of the two inputs to the mixer (phase detector). Then, the mixer (working as a phase detector) converts phase fluctuations to voltage fluctuations, which can then be read by the baseband Spectrum Analyzer as a frequency noise.
- The frequency noise is then converted as a phase noise reading.

The Frequency Discriminator method degrades the measurement sensitivity (at close-in offset frequencies) but is useful when the tested oscillator is a noisier source that has high-level, low-rate phase noise, or has high close-in spurious sidebands which can make problems for the phase detector PLL technique.
- A longer delay line will improve the sensitivity but the insertion loss of the delay line may exceed the source power available and cancel any further improvement.
- Longer delay lines limit the maximum offset frequency that can be measured.
- This method is best used for free-running sources such as LC oscillators or cavity oscillators.

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