

# Phase Noise in Oscillators

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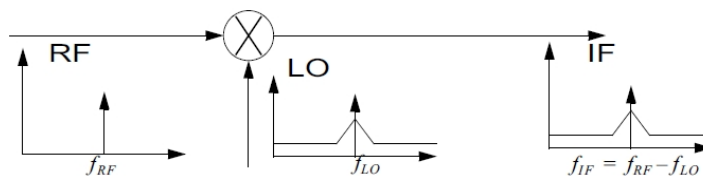
As well known from oscillator theory, two conditions are required to make a feedback system oscillate: the open loop gain must be greater than unity; and total phase shift must be  $360^\circ$  at the frequency of oscillation.

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

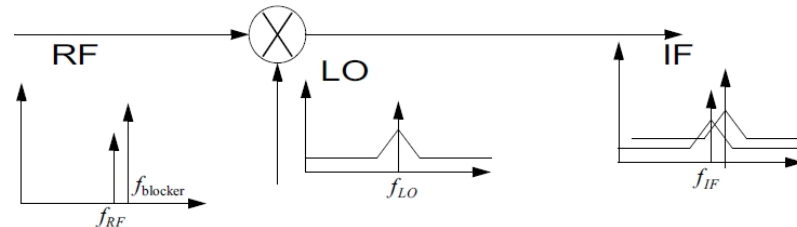
- Frequency Stability is a measure of the degree to which an oscillator maintains the same value of frequency over a given time.
- Phase Noise can be described as short-term random frequency fluctuations of a signal; is measured in the frequency domain, and is expressed as a ratio of signal power to 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 ( $90^\circ$  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.

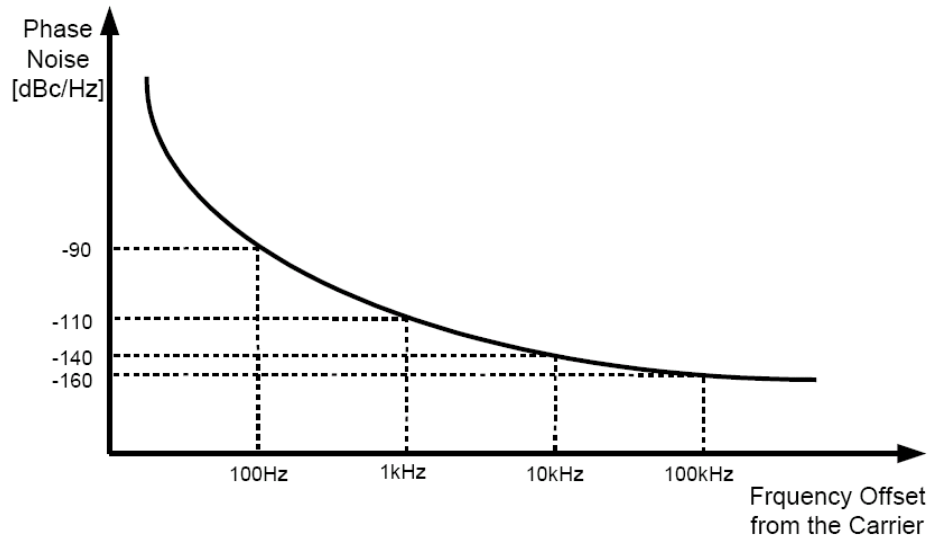


- The performance of some types of AM detectors or SSB detectors may be degraded by the local oscillator Phase Noise. Reciprocal mixing may cause the receiver noise floor to increase when strong signals are near the receiver's tuned frequency; this limits the ability to recover weak signals.
- Local 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  $45^\circ$  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  $\text{dBc}/\text{Hz}$  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.

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

$L_{PM}$  = 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,  $1.38 \times 10^{-23}$  [J/K]

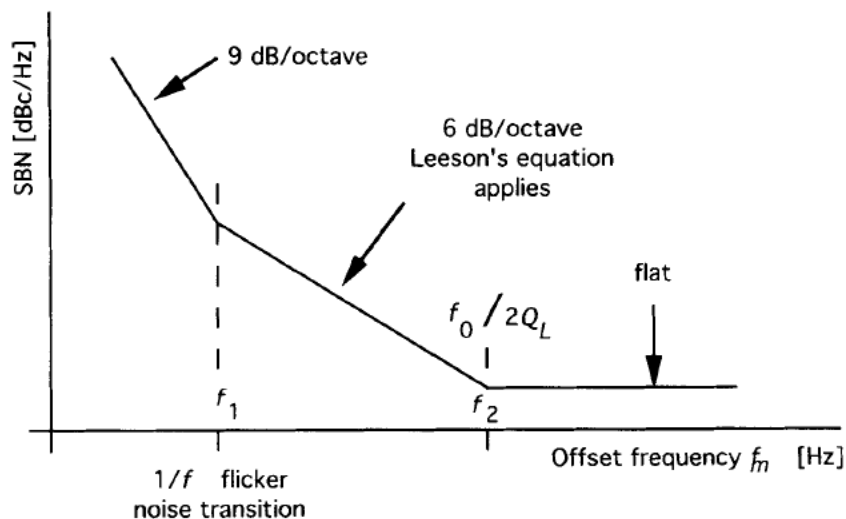
$T$  = Temperature [K]

$Q_L$  = Loaded-Q [dimensionless]

$f_0$  = 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.

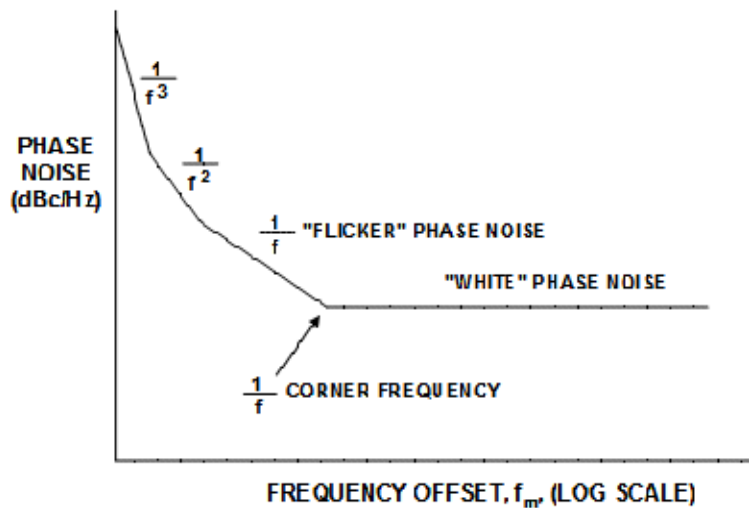
**Loaded-Q** represents the width of the resonance curve, or phase slope, including the effects of external components. In this case the Q is determined mostly by the external components.

- 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:

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

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 ( $Q_L = 0.5 \cdot Q_U$ ) that corresponds to a 6 dB 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 or 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 to 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  $90^\circ$  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 BJT's 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 ( $\sim 1\text{kHz}$ ), followed by BJTs ( $\sim 5\text{kHz}$ ), then CMOS ( $\sim 1\text{MHz}$ ), and GaAs are the worst ( $\sim 10\text{MHz}$ ).
- 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.
- 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  $-55^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$  the variation is  $\pm 3$  dB 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:

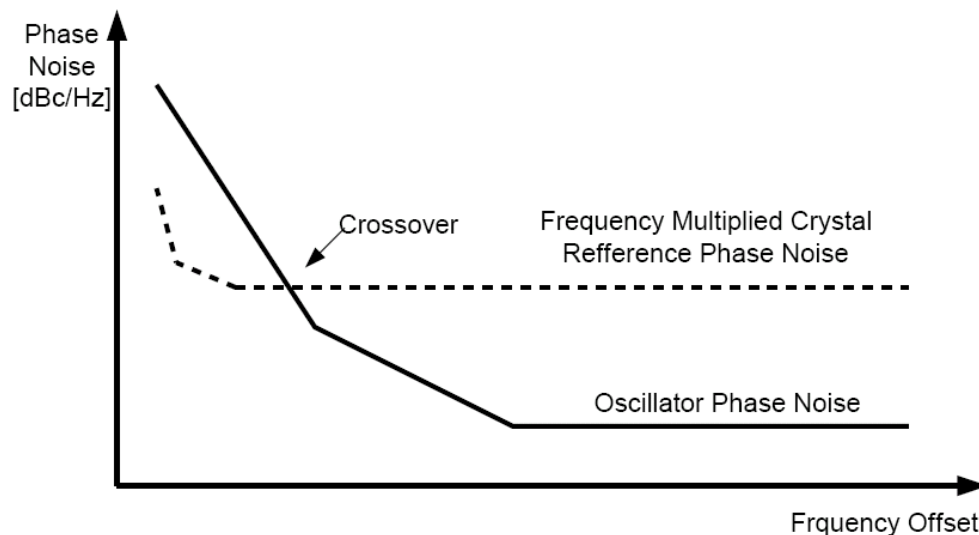
- The best oscillator transistor is a device with the lowest possible noise figure and lowest  $f_T$ . A commonly used criteria is:  $f_T \leq 2 * f_{osc}$ .
- Meantime, doing a trade-off, have to use a high frequency transistor having small junction capacitance and operate at moderately high bias voltage 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  $I_{c_{max}}$  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  $I_{c_{max}}$  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  $\Omega$  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.

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  $20 \cdot \text{LOG}(N_{VCO\_divider})$  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.
- 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;  $F_{\text{cutoff}} < (F_{\text{comparison}} / 10)$
- 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.

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