Phase Noise.

This is perhaps the most important parameter in many oscillators and it deserves an in-depth discussion on what it is, how it affects a system and how it can be minimised in an oscillator design.

1 Phase Noise

An oscillator can be considered as a filtered noise generator and therefore noise will surround the carrier, equivalent to random FM and AM modulations on the ideal RF sine wave - this additional noise is known as Phase Noise. If we consider the addition of a noise voltage to a sinusoidal voltage, we must take into account the phase relationship. A phasor diagram below can be used to explain the effect.

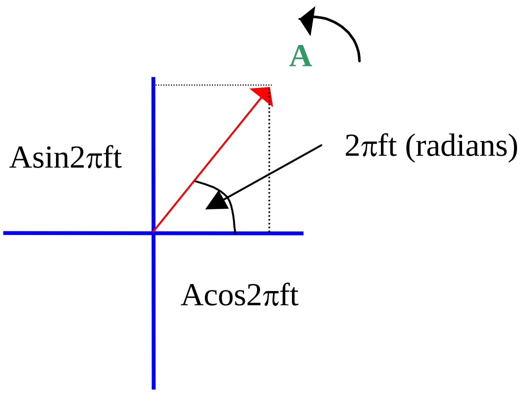


Figure 1 Phase noise phasor diagram. A phasor with amplitude A can have any value of phase from 0 to 360 degrees as represented by the phasor rotating around the origin. Including the phase component gives a phasor of value Asin(2πft) .

Noise contains components at many frequencies, so its phase with respect to the main carrier is random, and its amplitude is also random. Noise can only be described in statistical terms because its voltage is constantly and randomly changing, but it does have an average amplitude that can be expressed in RMS volts. Figure 2 shows noise added to the carrier phasor, with the noise represented as a fuzzy, uncertain region in which the sum phasor wanders randomly.

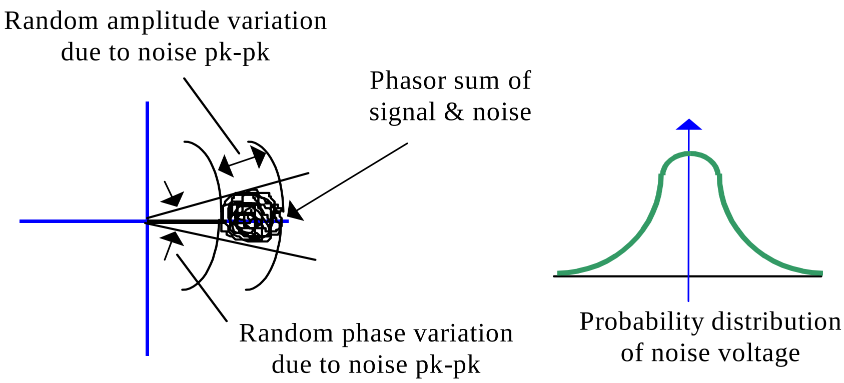


Figure 2 Phase noise added to a carrier. The phasor of figure 1 can also have a smaller phasor added to it due to noise. This additional random noise phasor will cause a 'circle' of random values which is phase noise added to the carrier.

The phase of the noise is uniformly random – no direction is more likely than any other – but the instantaneous magnitude of the noise obeys a probability distribution as shown.

2 How phase noise effects a system.

In transmitters local oscillator noise is amplified by the subsequent amplifier stages and is eventually fed to the antenna together with the wanted signal. The wanted signal is therefore surrounded by a band of noise originating from the phase noise of the local oscillator. Therefore the noise generated can spread over several kHz masking nearby lower power stations as shown in figure 3.

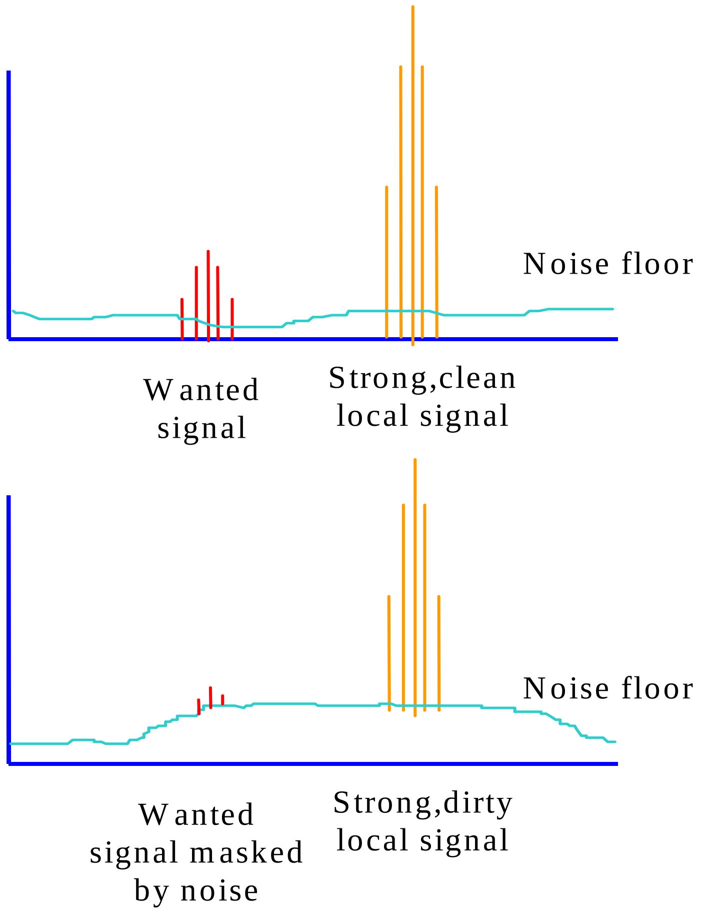


Figure 3 Transmitter spectrum for a clean and noisy local oscillator source. The lower diagram shows how a noisey local oscillator can raise the noise floor, swamping low power signals close to carrier.

The situation is more complicated with receivers and results in reciprocal mixing in the mixer. If we modulate a RF signal and mix it with a clean LO source a modulated IF signal will be the result. If, on the over hand, we mix a clean RF signal with a modulated LO source then again a modulated IF will be the result. To the listener the modulation will appear to be the same, as indeed it is. The effect can be explained by suggesting that the noise components are additional LO's that are offset from the main carrier. Each of them mixes other signals that are offset from the LO by the receivers IF. Noise is the sum of a infinite number of infinitesimal components spread over a range of frequencies, so the signal it mixes into the IF are spread into an infinite number of small replicas, all at different frequencies.

This amounts to a scrambling of these other weaker frequencies into the noise. It is for the reasons given that phase noise is a key design parameter for such applications as satellite repeaters, sensitive communication receivers and mobile phone base stations.

3 Limits on phase noise performance - Leeson's Oscillator Model

An oscillator can be considered as an amplifier with positive feedback and initially the contribution of the amplifier noise specified by its Noise factor can be considered.

Noise factor F is defined as follows:-

$$F = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{N_{out}}{N_{in}G} = \frac{N_{out}}{GkTB}$$

$N_{out} = FGkTB$ $\quad N_{in} = kTB$ where N_{in} is the total input noise power to a noise - free amplifier. The input phase noise in a 1-Hz bandwidth at any frequency $fo + fm$ from the carrier produces a phase deviation given by :-

$$\Delta\vartheta_{peak} = \frac{V_{nRMS1}}{V_{avs\,RMS1}} = \sqrt{\frac{FkT}{P_{avs}}} \quad ; \quad \Delta\vartheta_{1RMS} = \frac{1}{\sqrt{2}}\sqrt{\frac{FkT}{P_{avs}}}$$

Since a correlated random phase relation exists at $fo - fm$, the total phase deviation becomes

$$\Delta\vartheta_{1RMS\,total} = \sqrt{\frac{FkT}{P_{avs}}}$$

The spectral densisty of phase noise becomes

$$S_{\vartheta}(f_m) = \Delta\vartheta^2_{RMS} = FkTB/P_{avs}$$

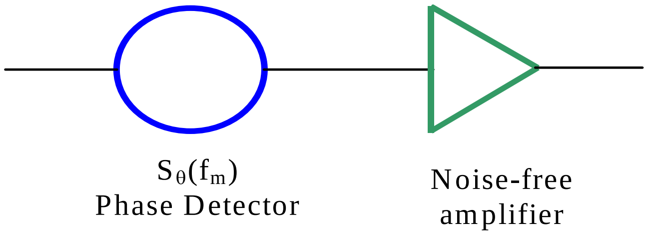
Where B = 1 for a 1-Hz bandwidth Using

$$kTB = -174 \text{ dBm/Hz} \quad (B = 1)$$

As an example, an amplifier with a +10dBm power at the input and a noise figure of 6dB gives :-

$$S_{\vartheta}(f_m > f_c) = -174 \text{ dBm} + 6 \text{ dB} - 10\text{dBm} = -178\text{dB}$$

The phase-noise can be modelled by a noise-free amplifier and a phase detector at the input, as shown below in figure 4.



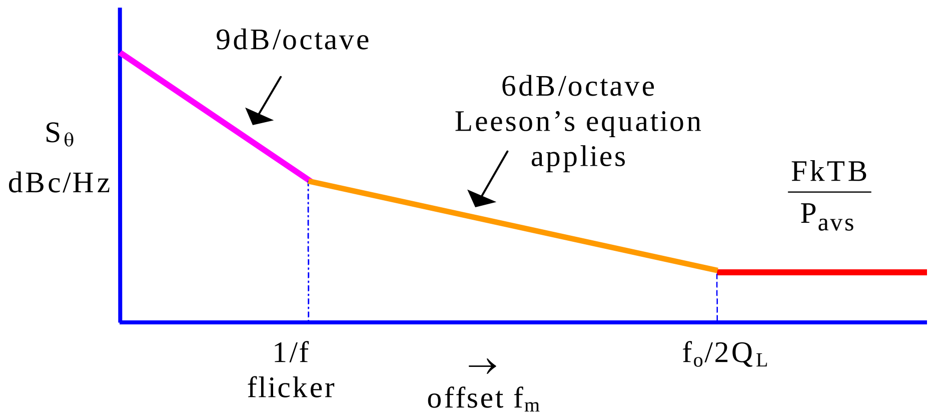


Figure 4 Representation of oscillator noise. The close to carrier noise with a slope of 9dB/octave is due to the flicker noise of the active device and has a cut-off at the flicker corner frequency of 1/f. The 6dB/octave section is due to phase noise according to Leeson's equation and is a function of loaded Q, noise factor, power, temperature. Above carrier offsets of $f_o/(2QL)$ noise is broad-band noise as defined by FkTB/(P_{avs}).

In reality the spectral purity of the carrier is affected by the device generated flicker noise at frequencies close to the carrier and shows a 1/f component with a corner frequency known as fc. The spectral phase noise can be given as:-

$$Sm(f_m) = \frac{FkTB}{P_{avs}}\left(1 + \frac{fc}{fm}\right) \qquad B = 1$$

B = frequency bandwidth (Hz)

T = temperature (degrees Kelvin)

Pavs = Average power in resonator (W)

fc = flicker corner frequency (Hz)

fm = frequency offset (Hz)

F = noise factor

k = Boltzman constant.

The phase noise at the input to the amplifier is likely to be bandwidth limited and in the case of an oscillator this is determined by the Q of the resonator and can be modelled as an amplifier with feedback as shown below in figure 5.

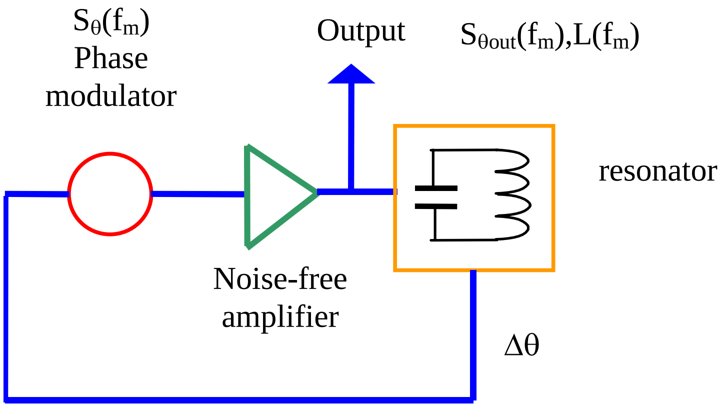


Figure 5 Model of an oscillator for noise analysis. The main components of the system are the resonator, a noise-free amplifier and a noise source (phase modulator).

The tank circuit or band pass resonator has a low-pass transfer function: -

$$L(\omega_m) = \frac{1}{1 + j\left(2Q_L \omega_m / \omega_o\right)}$$

Where QL= loaded Q ; ωm = carrier offset (rad/s) ; ωo = centre frequency (rad/s)

$\omega_o / 2Q_L = B/2$ is the half - bandwidth of the resonator.

These equations describe the amplitude response of a band pass resonator.

The assumption is that phase noise is transferred, without attenuation, through the resonator up to the half bandwidth. The closed loop response of the phase feedback is given by: -

$$\Delta\vartheta_{out}(f_m) = \left(1 + \frac{\omega_o}{j2Q_L\omega_m}\right)\Delta\vartheta_{in}(f_m)$$

The power transfer becomes the phase spectral density

$$S_{\vartheta out}(f_m) = \left[1 + \frac{1}{f_m^2}\left(\frac{f_o}{2Q_L}\right)^2\right]S_{\vartheta in}(f_m)$$

$$\text{where } S_{\vartheta in}(f_m) = \frac{FkTB}{P_{avs}}\left(1 + \frac{fc}{fm}\right)$$

$$\text{Finally } L(f_m) = \frac{1}{2}\left[1 + \frac{1}{f_m^2}\left(\frac{f_o}{2Q_L}\right)^2\right]S_{\vartheta in}(f_m)$$

$$L(f_m) = \frac{1}{2}\left[1 + \frac{1}{f_m^2}\left(\frac{f_o}{2Q_L}\right)^2\right]\frac{FkT}{P_{avs}}\left(1 + \frac{fc}{fm}\right)$$

where L(fm) = Phase noise (dBc/Hz)
Q_L = loaded Q
f_m = carrier offset frequency (Hz)
f_o = carrier centre frequency (Hz)
f_c = flicker corner frequency of the active device (Hz).
T = temperature (°K).
Pavs = Average power through the resonator (W).
F = Noise factor of the active device.
k = Boltzman constant

Multiplying out the expression: -

$$L(f_m)=\frac{FkT}{2P_{avs}}\left[1+\frac{fc}{fm}+\frac{1}{f_m^2}\frac{f_o^{\,2}}{4Q_L^{\,2}}+\frac{fc}{fm}\frac{1}{f_m^2}\frac{f_o^{\,2}}{4Q_L^{\,2}}\right]$$

$$L(f_m)=\frac{FkT}{2P_{avs}}\left[1+\frac{fc}{fm}+\frac{f_o^{\,2}}{4f_m^2Q_L^{\,2}}+\frac{f_o^{\,2}fc}{4f_m^3Q_L^{\,2}}\right]$$

This finally gives us the Leeson equation for single-sided phase noise density: -

$$L(f_m)=\frac{FkT}{2P_{avs}}\left[1+\frac{fc}{fm}+\left(\frac{f_o}{2f_mQ_L}\right)^2\left(1+\frac{fc}{fm}\right)\right]$$

Flicker effect

Resonator Q

Phase perturbation

Usually the phase noise is specified in dBc/Hz ie :-

$$L(f_m)=10\mathrm{Log}_{10}\left\{\frac{FkT}{2P_{avs}}\left[1+\frac{fc}{fm}+\left(\frac{f_o}{2f_mQ_L}\right)^2\left(1+\frac{fc}{fm}\right)\right]\right\}\quad \text{dBc/Hz}$$

The Leeson equation identifies the most significant causes of phase noise in oscillators. Therefore it is possible to highlight the main causes in order to be able to minimise them.

The relationship between loaded Q, noise factor and centre frequency can be used to derive the single-sideband phase noise performance, for a given frequency offset in the form of the nomograph shown in figure 5.

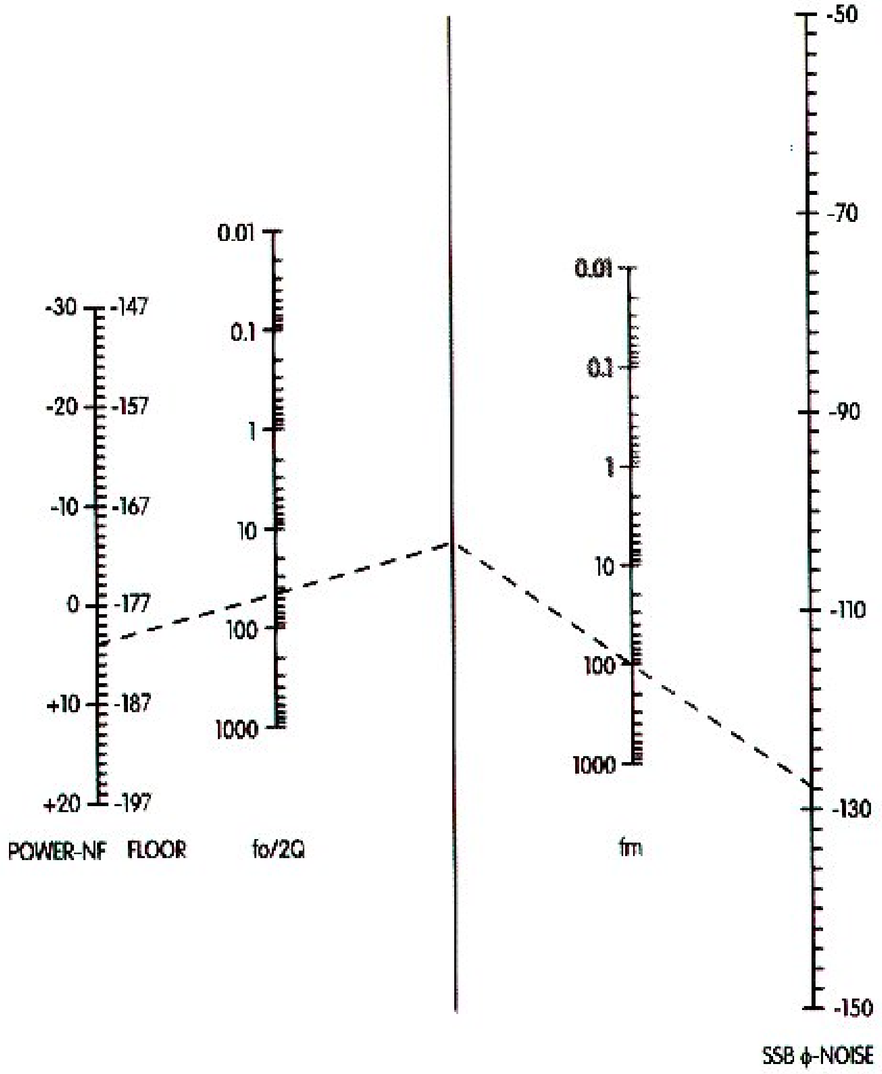


Figure 5 Nomograph for calculating the phase noise of an oscillator. The nomograph is valid for offset frequencies 1/fc to fo/(2Q_L), where fc = flicker corner frequency of the active device and QL = loaded Q of the resonator.

The Leeson equation was evaluated using an ADS model for phase noise by entering, temperature, output power, noise figure and loaded Q. The ADS schematic then uses a phase noise demodulator to produce the predicted phase noise of the oscillator. Figure 7 shows the ADS test bench setup for calculating the phase noise.

Figure 8 shows (a) a bipolar L-C oscillator and (b) a FET coaxial resonator oscillator.

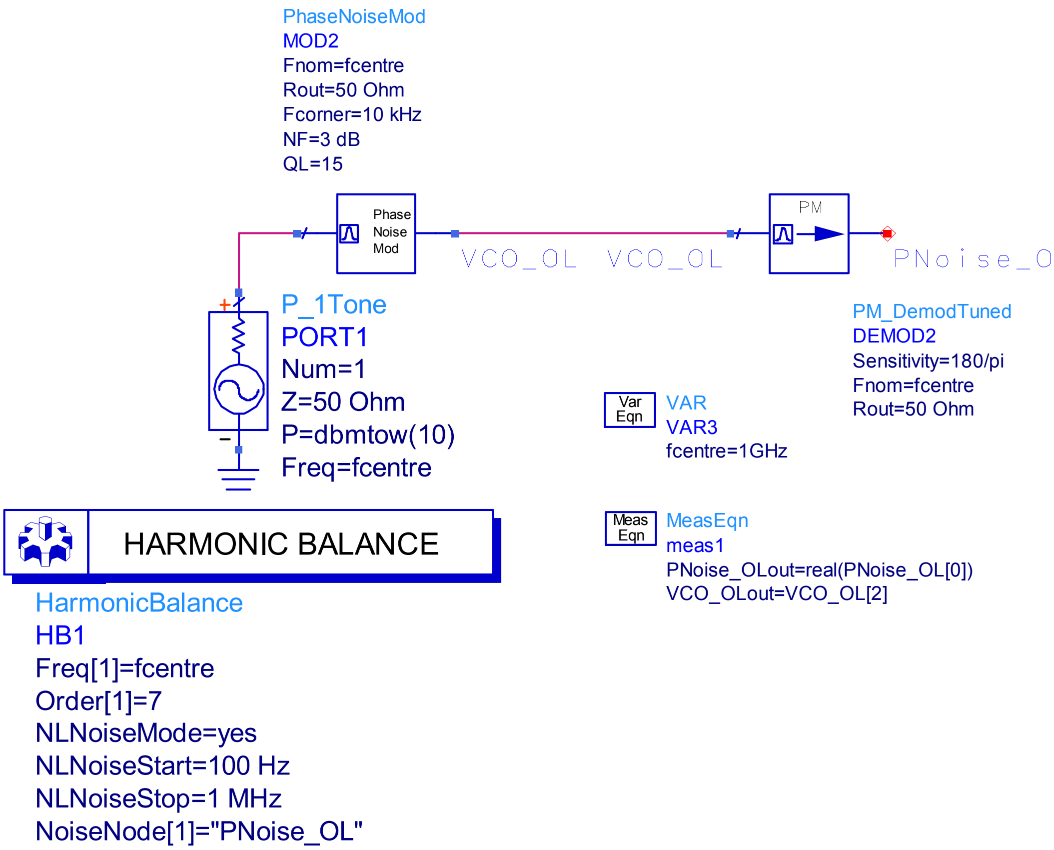


Figure 6 ADS circuit schematic for predicting the phase noise performance of an oscillator given the NF, loaded Q and flicker corner frequency. The P_1Tone block specifies the frequency (fcentre) and the oscillator power (10dBm). The Phase Noise modulator block simulates the noise generating from the oscillator based on NF, loaded Q and flicker corner frequency. The final block de-modulates the noise. The harmonic balance test set is set to measure non-linear noise. The NLNoise start and stop specify the Phase noise sweep range offset from the carrier and the noise node defines where to make the phase noise measurement (ie at the output).

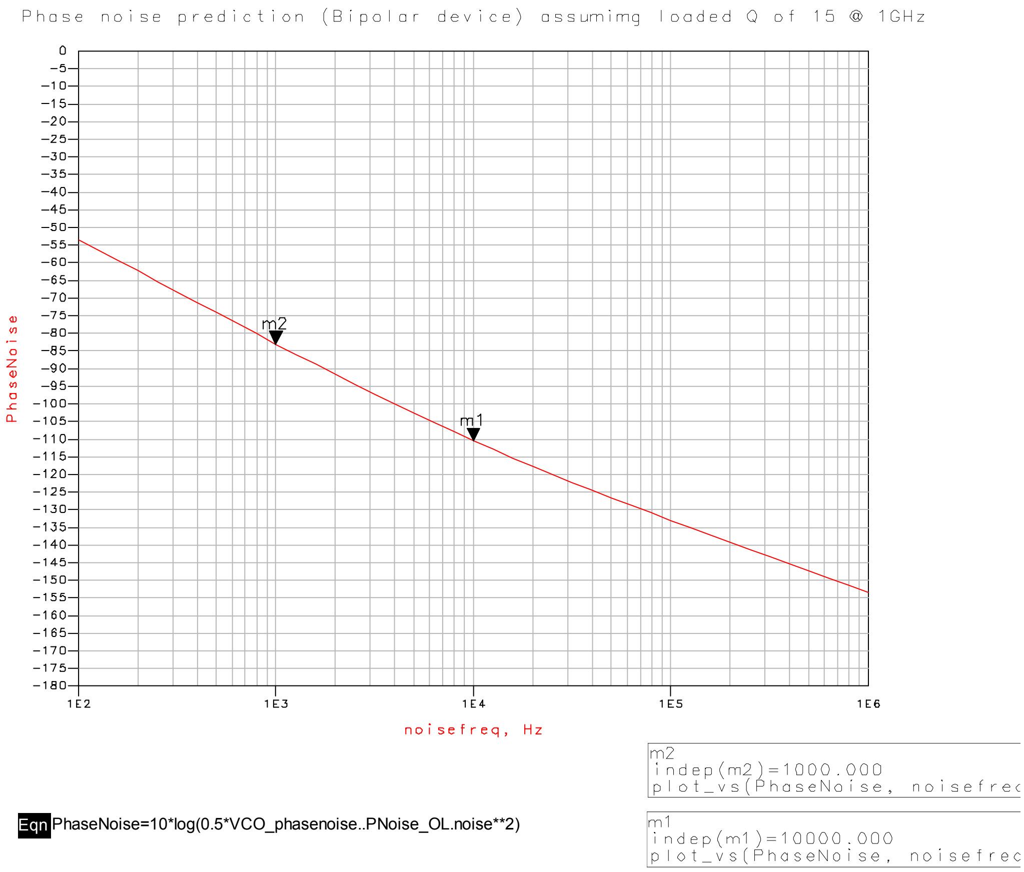


Figure 7 Phase noise prediction for a Bipolar Colpitts oscillator. The frequency is set to 1GHz and the loaded Q of the resonator is ~ 15. Note that the flicker noise is set to 10KHz which, is typical for a bipolar transistor.

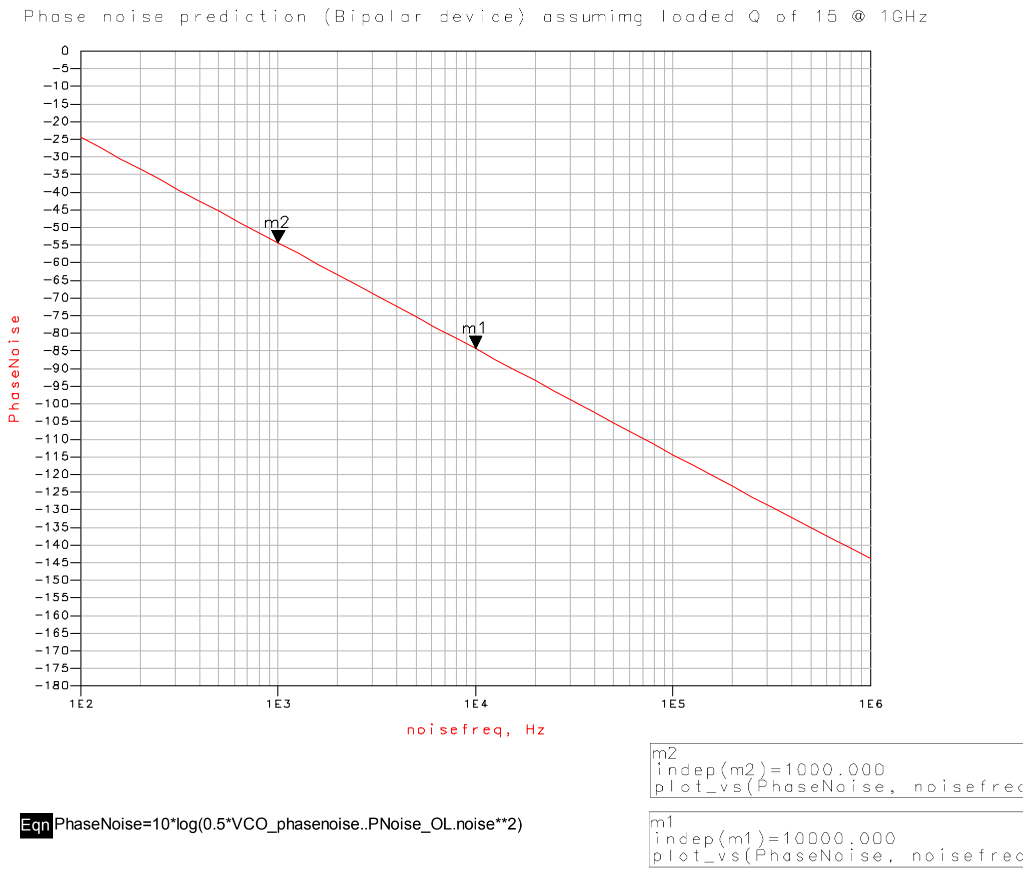


Figure 8 Phase noise prediction for a FET Reflection oscillator. The frequency is set again to 1GHz and the loaded Q of the resonator is ~ 15. Note that the flicker noise is set to 10MHz which, is typical for a MESFet transistor and dominates the phase noise of this oscillator.

The ADS simulations show how the phase noise is degraded close to the carrier by the addition of flicker noise especially for the GaAs FET device. We would therefore wish to maximise the loaded Q by using a coaxial or dielectric resonator. However this is all very well for a fixed frequency oscillator where we are able to maximise the Q, we generally require a variable frequency oscillator, (VCO) for use in a phase locked loop, to cover a band of frequencies. Such VCO's require a method of converting the PLL control voltage to frequency and this is normally done with a varactor diode (Vari-capacitance diode). Unfortunately any noise on the PLL control voltage and any internally generated noise will modulate the carrier, increasing the overall phase noise performance. The equivalent noise voltage modulating the varactor is given by Nyquist's equation:-

$$V_n = \sqrt{4kTR_{enr}} \quad \text{volts/root Hz}$$

The peak phase deviation in a 1 Hz bandwidth which results from the varactor noise resistance is:-

$\vartheta d = \dfrac{\sqrt{2}K_v V_n}{f_m}$ where K_v is the VCO gain constant in Hz/volt. The resulting phase noise in dBc/Hz is: -

$$L(f_m) = 20Log\frac{\vartheta d}{2} \quad \text{ie} \quad L(f_m) = 20Log\frac{\sqrt{2}K_v V_n}{2f_m}$$

Therefore, the total single-sideband phase noise will be the power sum of the oscillator phase noise given by the Leeson equation added to the varactor phase noise just given.

Varactor modulation noise is most significant in broadband high-frequency VCO's, because the VCO gain constant is large. The two following spreadsheet calculations show the addition of a varactor with a 10MHz/volt & 100MHz/volt varactor tuning range.

Figure 9 shows the phase noise prediction for a 1GHz VCO (NF=10dB P=10dBm and loaded Q = 50) with a varactor tuning range 10MHz/volt, while figure 10 shows a 1GHz VCO (NF=10dB;P=10dBm and loaded Q = 50) with a varactor tuning range 100MHz/Volt.

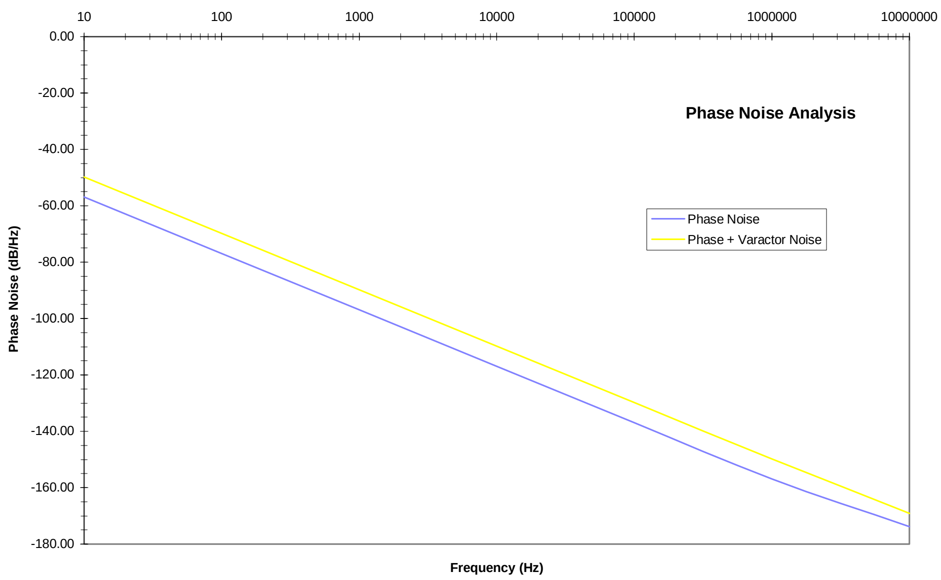


Figure 9 Phase noise prediction of a VCO with a varactor tuning range of 10MHz/volt. The VCO has the following parameters of noise figure =10dB, output power=10dBm and loaded Q = 50.

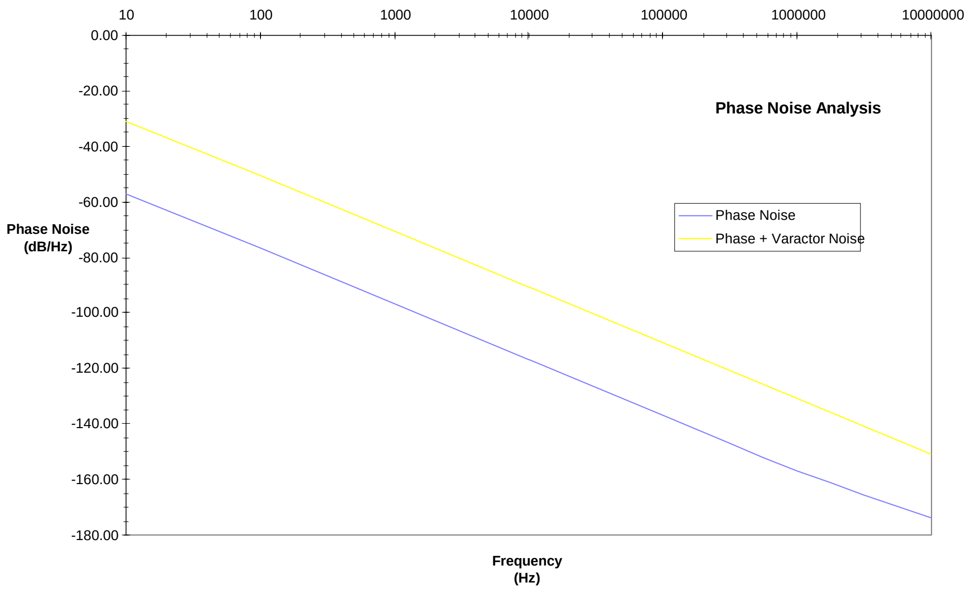


Figure 10 Phase noise prediction of a VCO with a varactor tuning range of 100MHz/volt. The VCO has the following parameters of noise figure =10dB, output power=10dBm and loaded Q = 50.

The previous examples show in the extreme varactor noise and flicker noise can dominate the main cause of noise in an oscillator – that generated by the resonator and specified by it's loaded Q.

In summary, in order to minimise the phase noise of an oscillator we therefore need to ensure the following:-

(1) Maximise the Q.

(2) Maximise the power. This will require a high RF voltage across the resonator and will be limited by the breakdown voltages of the active devices in the circuit.

(3) Limit compression. If the active device is driven well into compression, then almost certainly the noise Figure of the device will be degraded. It is normal to employ some form of AGC circuitry on the active device front end to clip and hence limit the RF power input.

(4) Use an active device with a low noise figure.

(5) Phase perturbation can be minimised by using high impedance devices such as GaAs Fet's and HEMT's, where the signal-to-noise ratio or the signal voltage relative to the equivalent noise voltage can be very high.

(6) Reduce flicker noise. The intrinsic noise sources in a GaAs FET are the thermally generated channel noise and the induced noise at the gate. There is no shot noise in a GaAs FET, however the flicker noise (1/f noise) is significant below 10 to 50MHz. Therefore it is preferable to use bipolar devices for low-noise oscillators due to their much lower flicker noise, for example a 2N5829 Si Bipolar transistor, has a flicker corner frequency of approximately 5KHz with a typical value of 6MHz for a GaAs FET device. The effect of flicker noise can be reduced by RF feedback, eg an un-bypassed emitter resistor of 10 to 30 ohms in a bipolar circuit can improve flicker noise by as much as 40dB.

(7) The energy should be coupled from the resonator rather than another point of the active device. This will limit the bandwidth as the resonator will also act as a band pass filter.