1

VCO Basics

1.1 Definitions

1.1.1 Frequency Tuning

A general VCO can be treated as a black box with an input V_{tune} and a periodic oscillating output $V(t)$ depicted as drawn in Fig. 1.1. The VCO is

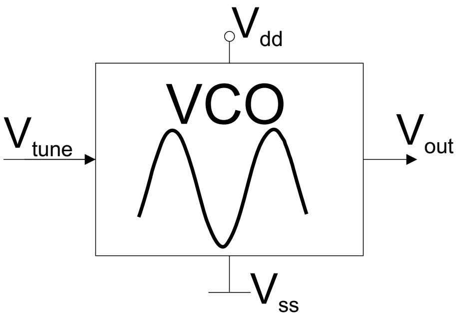

Fig. 1.1. Basic VCO

connected to the power supply through VSS and VDD. The output voltage $V_{out}(t)$, differential or single ended, is periodic:

$$V_{out}(t) = V_0 sin(\omega_c t + \varphi) \tag{1.1}$$

with phase φ, V_0 amplitude and angular carrier frequency

$$\omega_c(V_{tune}) = 2\pi f_c(V_{tune}) \tag{1.2}$$

which is dependent on the tuning voltage input V_{tune}, as a voltage controlled oscillator is needed. The frequency spectrum and time-domain output of an ideal oscillator is shown in Fig. 1.2.

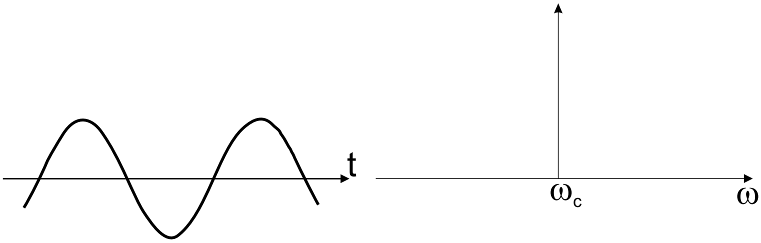

Fig. 1.2. Ideal oscillator output over time and corresponding frequency spectrum

1.1.2 VCO-Gain

VCOs are normally used in a phase locked loop (PLL) as voltage to frequency translation block. The transfer function of input voltage to output frequency

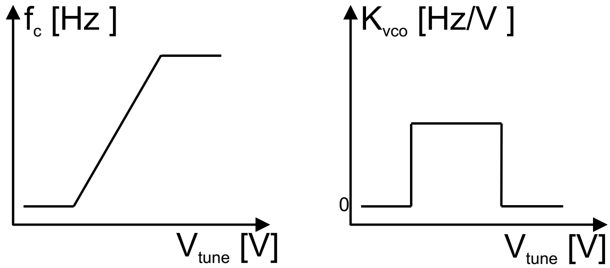

Fig. 1.3. VCO frequency transfer function

(e.g., Fig. 1.3) and its gain K_{VCO} is of main importance for PLL design (more in section 1.1.5).

$$K_{VCO} = \frac{d\,f_c}{d\,V_{tune}} \tag{1.3}$$

1.1.3 Pushing

Similarly as in the previous section, the transfer function from power supply to output frequency can be defined as:

$$K_{Vdd} = \frac{df_c}{dV_{dd}} \tag{1.4}$$

$$K_{Vss} = \frac{df_c}{dV_{ss}} \tag{1.5}$$

Unfortunately K_{Vdd} and K_{Vss} are not zero in real oscillators and can lead to severe problems if not specified at the very beginning design phase of a VCO.

1.1.4 Pulling

VCO output frequency also varies with the load attached to its output. This is called load pulling:

$$pulling = \frac{\Delta f_c}{\Delta load} \tag{1.6}$$

This parameter is mainly of concern for VCO-modules and usually defined for changing the VSWR of the load from 1 to 2 (see e.g [6]).

1.1.5 Phase Noise and Jitter

Definitions

As already stated, an ideal sinusoidal oscillator is described as

$$V_{out}(t) = V_0 cos[2\pi f_c t + \phi] \tag{1.7}$$

with constant amplitude V_0, center frequency f_c, and ϕ a fixed phase. In the frequency domain the spectrum of this oscillator consists of a Dirac-impulse at $\pm f_c$. A real oscillator is more generally given by

$$V_{out}(t) = V_0(t) y[2\pi f_c t + \phi(t)]. \tag{1.8}$$

y is a periodic function. The fluctuations introduced by $V_0(t)$ and $\phi(t)$ - now functions in time - result in sidebands close to f_c, with symmetrical distribution around f_c (Fig. 1.4) [11]. The frequency fluctuations correspond to jitter in the time-domain, which is a random perturbation of zero-crossings of a periodic signal (Fig. 1.5). Frequency fluctuations are usually characterized

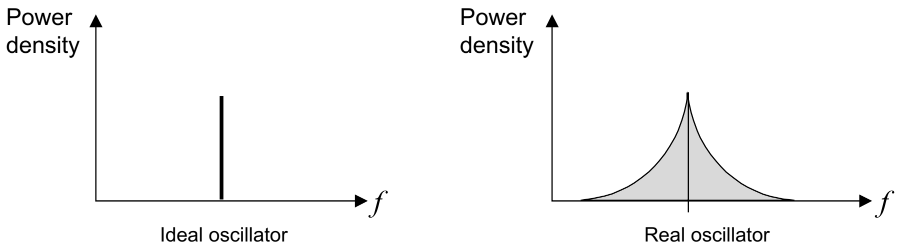

Fig. 1.4. Frequency spectrum of ideal and real oscillators

by the single sideband noise spectral density normalized to the carrier signal power (Fig. 1.4). It is defined as

$$\mathcal{L}_{total}(f_c, \Delta f) = 10 \log \left[\frac{\mathcal{P}_{sideband}\,(f_c + \Delta f, 1\,\mathrm{Hz})}{\mathcal{P}_{carrier}} \right] \tag{1.9}$$

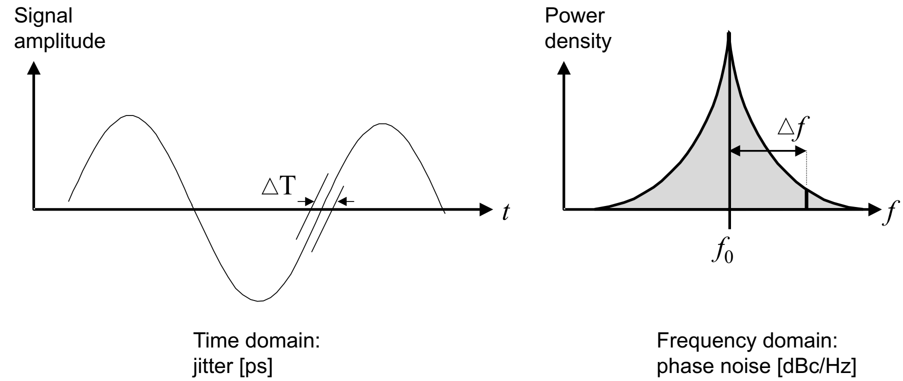

Fig. 1.5. Jitter in the time domain relates to phase noise in the frequency domain

and has units of decibels below the carrier per hertz (dBc/Hz). $\mathcal{P}_{carrier}$ is the carrier signal power at the carrier frequency f_c and $\mathcal{P}_{sideband}(f_c + \Delta f, 1\,\mathrm{Hz})$ denotes the single sideband power at the offset Δf from the carrier f_c at a measurement bandwidth of 1 Hz.

The total phase noise $\mathcal{L}_{total}$ includes both amplitude $A(t)$ and phase $\phi(t)$ fluctuations. In practical oscillators the amplitude is limited by non-linear active devices and $\mathcal{L}_{total}(f_c, \Delta f)$ is dominated by the phase part of the phase noise [11, 55].

The time domain equivalent or jitter is characterized as the statistical distribution of the output signal period. This typically is assumed of gaussian distribution with mean value $\tau = 1/\omega_c$ and variance σ. The relation between clock jitter σ_τ and phase noise can be calculated as [11]:

$$\sigma_\tau^2 = \frac{4}{\pi {\omega_c}^2} \int_0^\infty S_\phi \omega \sin(\frac{\omega \tau}{2}) d\omega \tag{1.10}$$

with τ the clock period.

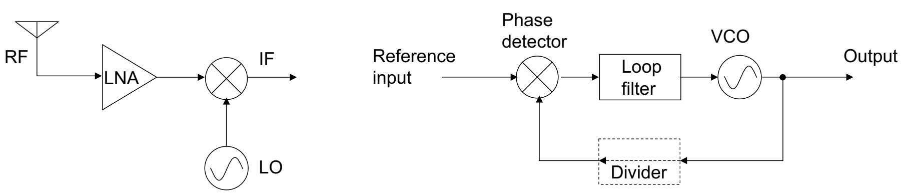

Fig. 1.6. Simplified receiver block diagram *(left)* and phase-locked loop *(right)*

Importance of Phase Noise

The front-end of a typical receiver is shown in Fig. 1.6, where a mixer and a local oscillator (LO) downconvert the incoming radio frequency (RF) signal to a lower, intermediate frequency (IF). With a LO frequency lower than the RF frequency (low-side LO) the resulting intermediate (IF) frequency is determined by: $f_{IF} = f_{RF} - f_{LO}$. To achieve absolute synchronization of the LO signals, the VCO is engaged in a phase-locked loop (PLL, Fig. 1.6). A typical PLL consists of a VCO, a frequency divider, a phase detector, a charge pump, and a low-pass loop filter. It forces the output frequency to be equal to a multiple of the input reference frequency [11, 55]. PLL design is eased significantly with a VCO offering a linear dependence between tuning voltage and frequency. To understand the importance of phase noise Fig. 1.7 depicts

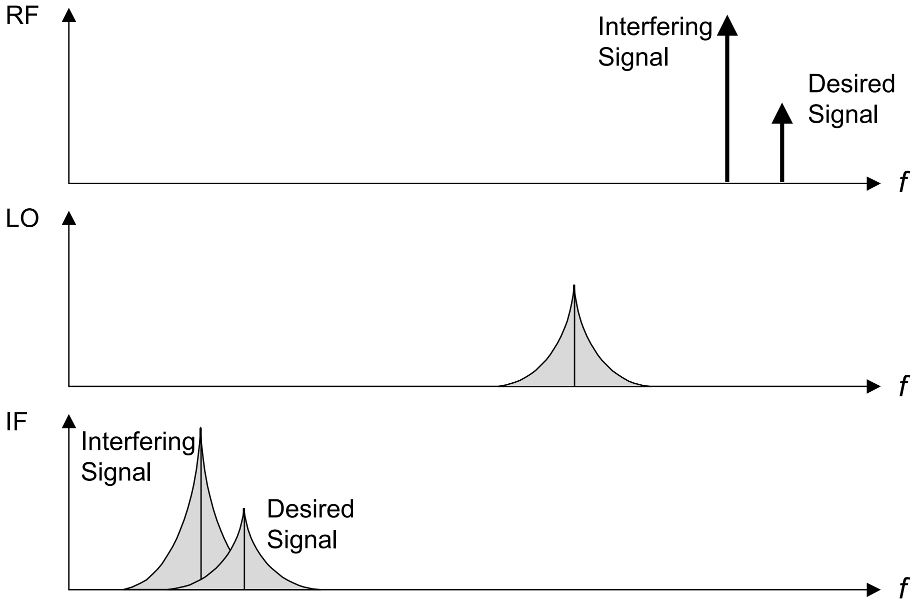

Fig. 1.7. Effect of oscillator phase noise in a receiver

the situation in a receiver. The LO signal used for downconversion has a noisy spectrum. Besides the wanted signal with small power an unwanted signal with large power is present in an adjacent channel (at a close-by frequency). After mixing with the LO the downconverted spectrum consists of two overlapping spectra. The wanted signal suffers from significant noise due to in-band signal from the downconversion of the interferer by the LO sideband: the signal-to-noise ratio is degraded [56]. In order to be able to detect the signals from all channels while (stronger) interferers may be present stringent phase noise specifications have to be met in wireless communication systems.

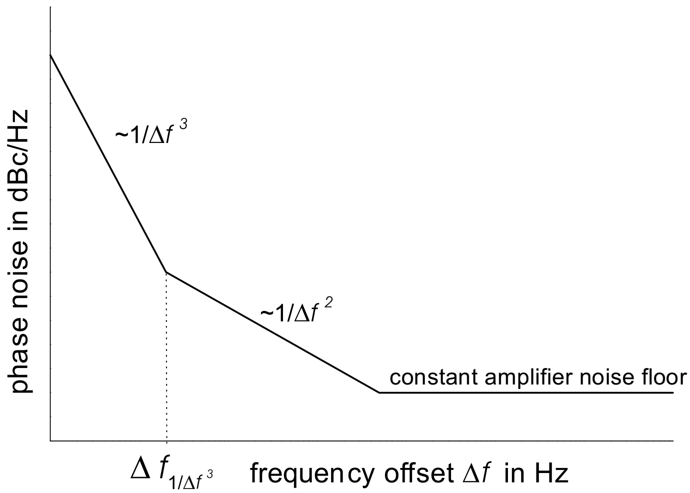

Fig. 1.8. Typical phase noise spectrum of a LC-oscillator

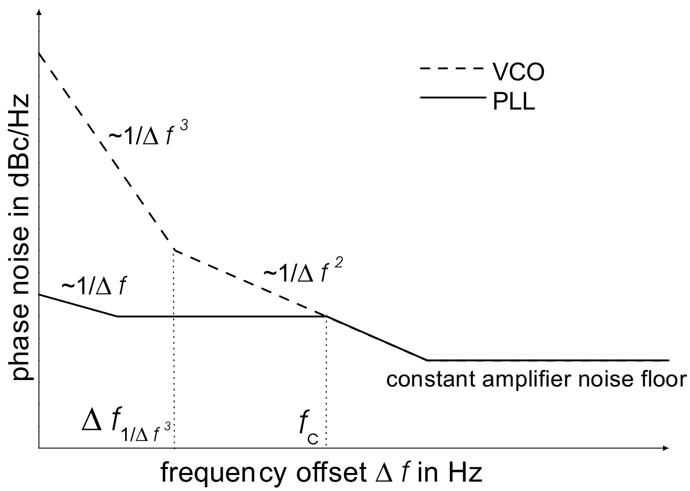

Fig. 1.9. Noise spectra of the VCO and the resulting PLL output

Phase Noise and The Impact on PLL Noise

A typical single side band phase noise spectrum is given in Fig. 1.8 [11, 55]. At low offset frequencies up to a corner frequency $\Delta f_{1/\Delta f^3}$ a $1/\Delta f^3$ behavior, also called flicker-noise behavior, is observed. For medium offset frequencies the phase noise shows a $1/\Delta f^2$-dependence, also called white-noise behavior, up to where the constant amplifier noise floor begins to dominate. PLL noise is mainly determined by noise introduced by the reference signal and the VCO. A thorough analysis of the transfer characteristic and loop response to noise signals shows that the PLL functions as high-pass for the noise from the VCO [55]. Above a cut-off frequency f_c, noise passes unattenuated. f_c is determined by the overall forward gain of the loop and the order of the divider [55]. Due to the existence of many adjacent channels specifications for the maximum PLL noise output have to be met. Figure 1.9 compares the spectra of the VCO noise and the resulting PLL noise output. Below f_c the output characteristics are dominated by the PLL transfer function. Output noise is significantly reduced compared to the "input" from the VCO. Above f_c essentially the VCO noise will be observed. Below f_c the resulting PLL noise is determined by the PLL design and the VCO phase noise, which can be exploited to suppress the flicker-noise region of VCO phase noise through adequate PLL design.

Table 1.1. VCO specification list

spec	**Unit**
Center frequency	GHz
Tuning Range	MHz
Phase noise	dBc/Hz @ offset [kHz]
Power consumption	mW
Supply voltage	V
VCO-Gain	MHz/V
Pulling	MHz/load-spec
Pushing	MHz/V
Area	μ m ^{2}
Cost	$
Operating temperature	$^\circ$C
Manufacturability	
Yield	%
Lifetime	Years

1.2 Requirements

Table 1.1 summarizes the general specifications for (integrated) VCO design. Main specifications are center frequency, tuning range, power supply voltage, power consumption and phase noise specifications. But additional specifications like cost or chip area, pulling, pushing, etc. must be fulfilled aiming at products in CMOS. For instance, a reliable operation over many years can only be met when taking into account all limits of a given CMOS technology, including the maximum allowed gate oxide voltages. Especially the pushing problem is often neglected, although it easily becomes a critical problem for the performance of a fully integrated synthesizer. Very few pushing data are included in the common VCO literature. However, typical pushing behavior is clearly documented and specified for real products, e.g. VCO modules [5, 6]. Also pulling usually is not treated, but this problem is less severe and mainly concerns careful output buffer design.

1.3 Integrated VCO Circuit Options

1.3.1 Ring Oscillators

A classical oscillator circuit solution is the connection of amplifiers or inverting in a ring of amplifiers or inverters. If the phase shift over the ring is 360 °, it will oscillate. An exemplary appliction is shown in Fig. 1.10. Ring oscillators

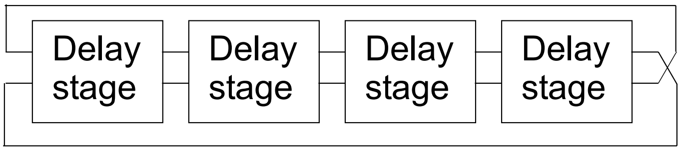

Fig. 1.10. Exemplary ring oscillator topology

have a very small area and are easy to integrate and design. They feature wide tuning ranges. Main disadvantage is their high power consumption and phase noise [21, 55, 94, 99]. Recent work, e.g. [21], show that it is possible to design low phase noise ring-oscillator's, but still at a much higher power consumption than for LC-VCOs.

1.3.2 LC Oscillators

A general LC-VCO can be symbolized as in Fig. 1.11. The oscillator consists of an inductor L and a capacitor C, building a parallel resonance tank, and an active element -R, compensating the losses of the inductor (R_L in Fig. 1.11)

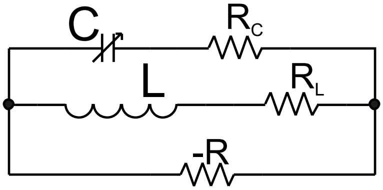

Fig. 1.11. Basic LC-VCO

and the losses of the capacitor (R_C in Fig. 1.11). The circuit results into an oscillator with angular center frequency.

$$\omega_c = \frac{1}{\sqrt{LC}} \tag{1.11}$$

As the capacitance C is proportional to the tuning voltage input V_{tune}, also ω_c is dependent on V_{tune} and the oscillator results in a voltage controlled oscillator. The capacitor C in Fig. 1.11 not only consists of a variable capacitor to tune the oscillator, but it also includes the parasitics or fixed capacitances of the inductor, the active elements, and of any load connected to the VCO (output driver, mixer, prescaler, etc.).

In comparison to ring oscillators, LC oscillators have a rather limited tuning range, but feature lower phase noise at a lower power consumption. The area of an LC oscillator with an integrated coil is much bigger than the area of a ring oscillator. This holds for designs aiming at widely spread GSM, UMTS, DCS1800, ... applications in the frequency range of 900 MHz to 2 GHz, for higher frequency upcoming applications as WLAN (5.2 GHz, 5.7 GHz, 17.2 GHz) coil area is not important any more, as the coil size decreases with higher frequencies.

1.4 VCO Figure of Merit

The performance of VCOs is difficult to compare as they feature different center frequencies, power consumption P_{supply}, and phase noise over offset-frequency. A widely accepted figure of merit has been introduced in [85]:

$$\mathrm{FOM} = \mathcal{L}(f_0, \Delta f) + 10 \log \left(\left(\frac{f_0}{\Delta f} \right)^2 \frac{P_{supply}}{[mW]} \right). \tag{1.12}$$

where $\mathcal{L}(f_0, \Delta f)$ is the single-side-band noise at the offset frequency Δf from the carrier frequency f_0. This FOM is a direct deviation of Leesons empirical phase noise ([33], Eqn. (3.10)) expression normalized to the power consumption. For a fair comparison the worst-case measured phase noise of a VCO-design should be taken into account (unfortunately many authors tend to calculate a best-case FOM at, e.g., zero tuning voltage input). The performance of a VCO is regarded to be better with a more negative value or higher absolute value of the figure of merit.

1.5 Summary

This chapter summarized general definitions concerning the VCO design and a long list of requirements to oscillators.
To fulfill the very tough combination of low power consumption (battery operation) and ultra-low phase noise needed for telecommunications, the remaining text limits the subject to LC-VCO circuits, as generally their phase noise performance is superior to the phase noise of, e.g., ring-oscillators.

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