5 Design for Low Thermal Phase Noise

1 Introduction

A single chip radio remains a challenging problem due to technology limitations on passive component quality and lack of efficient optimization procedures. Of all RF blocks, voltage controlled oscillators, VCOs, have received highest attention in recent years as evidenced by the large number of publications reporting improving performance [1][2], higher operating frequency [3] or using a different passives technology to achieve the stringent requirements of wireless standards [4]. Integrated LC oscillator circuits published so far use tuning inductors that are fully integrated, partly integrated, or discrete, with quality factors spanning a large range. However, lacking a clear understanding of the physical processes of phase noise, it is difficult to compare the relative merits of these VCOs in a normalized sense. In this chapter, we present a non-exhaustive set of differential CMOS LC oscillators illustrating a systematic design methodology that builds on the phase noise theory presented earlier.

1.1 Oscillator Figure of Merit

The design space of LC oscillators entails phase noise, power consumption and oscillation frequency, and to a lesser degree, tuning range. These design dimensions are not always orthogonal and a well-formed cost function is necessary for comparing the relative merits of various designs. The best definition of a normalized Figure Of Merit (FOM) proposed so far is [5]:

$$\mathrm{FOM} = \left(\frac{\omega_o}{\omega}\right)^2 \frac{1}{\mathcal{L}(\omega)P} \tag{1}$$

where P is the power consumption in mW, $\mathcal{L}(\omega)$ is the phase noise at an offset ω from a center frequency ω_o.

The appeal of this definition is that it relates and normalizes the quantities given by Leeson's proportionality. The power of two in the frequency offset dependence indicates that flicker noise-induced phase noise is not normalized, suggesting that the FOM is useful only in comparing oscillators at large-enough offsets such that flicker noise is not the dominant source of phase noise. This chapter focuses on minimizing thermal noise's impact on oscillator phase noise. The FOM described above will be used as the inverse cost function to be maximized.

2 Note About Harmonic Balance in LC Oscillators

The LC tank, assuming no losses, is a typical physics textbook oscillator. Magnetic energy in the inductor converts to electric energy in the capacitor and vice versa. The oscillation is governed by the energy equation, which states that the total energy stored on the capacitor and in the inductor is constant.

The energy balance equation is not sufficient to describe the oscillation. The reason for that is the need to know the total oscillator energy, which is set by the initial current in the inductor and the initial voltage on the capacitor.

In practical oscillators, there are losses that must be overcome if the oscillation is to continue forever. In LC oscillators, the losses are overcome by employing a negative resistance, which in practice is implemented with one or more nonlinear components. They are represented in Figure 1 as the "non-sinusoidal" current source. The negative resistance current enters the tank and builds an oscillation amplitude that equals the product of the tank resistance at resonance and the fundamental of the current waveform.

$$A = RI_{\text{fund}} \qquad (2)$$

The capacitor offers little impedance to the harmonics of the injected current flow. On the other hand, the inductor impedes the harmonics from passing through it. The fundamental of the injected current flows only through the resistor since the inductor and the capacitor represent an open circuit at resonance. Only the reactive current can flow through the tank. The power in the