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OSCILLATOR DESIGN EFFICIENCY: A NEW FIGURE OF MERIT FOR OSCILLATOR BENCHMARKING

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ABSTRACT

A novel figure of merit (FOM) is proposed which allows absolute benchmarking of the carrier to noise ratio (CNR) of oscillators. Called Oscillator Design Efficiency (ODE), this FOM allows absolute comparison of designs. This is realized by comparison of a realized design with the best case (theoretical) oscillator design. In this comparison, ODE takes into account power dissipation, frequency and technology of the resonator. Furthermore, ODE gives the designer a good indication of how much room for CNR improvement is available compared to the best theoretical design. Finally, ODE provides a consistency check. Whenever ODE is greater than 0 dB or 100%, the theoretical CNR limit is crossed. In this situation the parameters, simulation results or measurements should be checked. Application of ODE will be demonstrated using 9 recently published integrated LC oscillator designs.

1. INTRODUCTION

Figures of Merit (FOMs) can be most helpful for a designer since they combine many parameters in one meaningful figure. Good examples are the technology FOMs like transistor bandwidth f_a, transition frequency f_t or the unity power gain frequency f_{max}. Although these FOMs only cover certain aspects of the technology, they give the designer an excellent benchmarking tool and a quick first order assessment of the optimum bias current for the active devices.

In electronic oscillators, CNR, power dissipation, operating frequency and tuning range are all related. During the design of an oscillator, a FOM which indicates how much room for CNR improvement there is, would help the designer. Clearly, this FOM should take into account the operating frequency, power dissipation and technology. The inclusion of all three aspects would help the designer to achieve an optimal and balanced design. A FOM can also be very useful to compare or benchmark various oscillator designs. One example is the oscillator number [1, 2] which is defined as:

$$FOM_1(f_o) = CNR_{design}(f_m) + 10\log\left[\left(\frac{f_o}{f_m}\right)^2\right] \qquad (1)$$

Here CNR_{design} is the simulated or measured CNR at offset frequency f_m of carrier frequency f_o, of a specific oscillator design. FOM_1 describes with its $(1/f_m)^2$ term the most important CNR-region of the oscillator. Due to this dependence, this FOM does not depend on a (arbitrarily chosen) value of f_m. However, it does not take into account that the CNR of an oscillator with a given noise level, can be improved by increasing the power of the carrier. And that this increase usually results in a higher value of the supplied power P_{DC}. This design aspect is taken into account in an improved version of FOM_1 [3, 4], namely

$$FOM_2(f_o, P_{DC}, P_{ref}) = -CNR_{design}(f_m) + 10\log\left[\left(\frac{f_m}{f_o}\right)^2 \frac{P_{DC}}{P_{ref}}\right] \qquad (2)$$

Here P_{DC} is the DC power dissipated by the oscillator and P_{ref} a reference power level normalizing the VCO dissipation to, for example,1 mW. Hence, FOM_2 has the fundamental disadvantage that it can give only relative ranking of oscillator designs because it depends on an arbitrary choice of P_{ref}.

With the FOM proposed in this paper an attempt is made to achieve an **absolute** benchmarking of the active part of oscillator designs. This FOM is called Oscillator Design Efficiency (**ODE**). ODE compares each design to the best theoretical limiting case of a design based on well-characterized components of the tank circuit. The advantages of the absolute benchmarking offered by ODE will be demonstrated by benchmarking 9 recently published LC oscillator designs.

2. OSCILLATOR DESIGN EFFICIENCY

ODE compares the CNR of a realized oscillator design with a theoretical best case design. Because ODE is an *efficiency* its value can range from 0 to 100% or alternatively, from $-\infty$ to 0 dB. Expressed in dB, equation 3 defines oscillator ODE.

$$ODE(Q_u, P_{DC}, f_o) = CNR_{design}(f_m) - CNR_{limit}(Q_u, P_{DC}, f_o, f_m) \qquad (3)$$

CNR_{limit} is explained and verified in the next section and given as:

$$CNR_{limit}(Q_u, P_{DC}, f_o, f_m) =$$

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$$-10\log\left[\frac{kT}{2P_{DC}}\frac{1}{Q_u^2}\left(\frac{f_o}{f_m}\right)^2\right] \quad (4)$$

In equation 4 the following parameters are used:

- P_{DC}: DC power dissipation of the VCO core (thus excluding, for example, output buffers). More accurate would be carrier power, but this is often not directly measured or reported in literature. Taken P_{DC} instead of the carrier power assumes 100% efficiency in DC to RF carrier power conversion. If this efficiency is specified it sets a limit to the maximum achievable ODE, since ODE will equal or less than the oscillator DC to RF carrier power efficiency.
- Q_u: Unloaded quality factor. More accurate would be loaded quality factor. However, this figure is often much more difficult to establish and often not reported in literature.
- f_o: Oscillation frequency.
- f_m: Offset frequency from carrier frequency f_o where the CNR is simulated or measured in a 1 Hz bandwidth.
- T: Absolute temperature in Kelvin during CNR simulation or CNR measurement. $T = 273.16 + P_{room}$ with room temperature P_{room} in $°C$.
- k: Boltzmann's constant: 1.38062×10^{-23}.

3. DERIVATION OF CNR_{LIMIT}

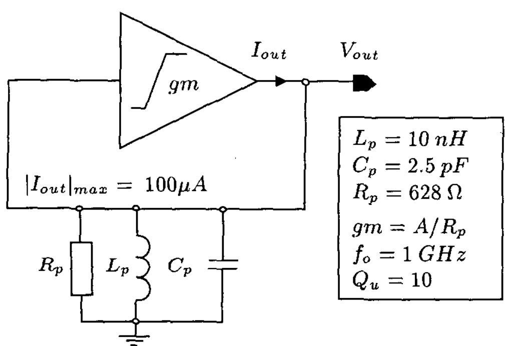

Figure 1. Non-linear oscillator model used for behavioral level simulations.

The derivation of CNR_{limit} is based on a limiting (best) case of an oscillator (figure 1), which consist of a passive part (tank circuit) characterized by Q_u and f_o, and a noiseless active part characterized by an open loop amplification A and a power consumption P_{DC}. The open loop amplification A is usually significantly larger than one in practical, robust designs. In this section the influence of A on the theoretical limit of CNR is investigated. This is done in two ways:

1. $CNR_{limit}(Q_u, P_{DC}, f_o, f_m)$ for the limiting case A equal to one, has been derived analytically in **appendix A**.
2. For $A > 1$, CNR_{limit} has been calculated with a numerical noise analysis program (RFspectre) applied to a specific choice of the parameters of the active and passive part (see figure 1).

Simulation results for open loop gain A ranging from 1.07 (larger than 1 for start-up) to 5 are presented in figure 2. As expected, the carrier approaches its maximum amplitude of $4/\pi \times |I_{out}|_{max} \times R_p = 80\ mV_{peak}$ as A increases. Hence, a high gain A yields in limiting case, a carrier voltage increase of 2.1 dB compared to the linear case A equal to 1. Since CNR_{limit} assumes 100 % DC to RF power conversion efficiency, this improvement is taken into account in the ODE definition.

The lower graph in figure 2 shows the simulations results of the phase noise at 1 MHz offset of the 1 GHz carrier. In the noise simulation noise increase due to folding effects are omitted. With open loop gain $A = 1$, the analytical phase noise at 1 MHz offset equals 114 $nV/\sqrt{Hz}$. Figure 2 shows that the phase noise does not decrease by the non-linear behavior of the oscillator. Apart from some minor numerical fluctuations the noise stays constant for A ranging from 1.07 to 5. Baseband up-conversion and down mixing of noise around harmonics of the carrier are omitted in the definition of CNR_{limit}, but will add to the total phase noise in practice. From figure 2 it can be concluded that CNR_{limit} with $A = 1$ defines the theoretical upper limit of the CNR for oscillators.

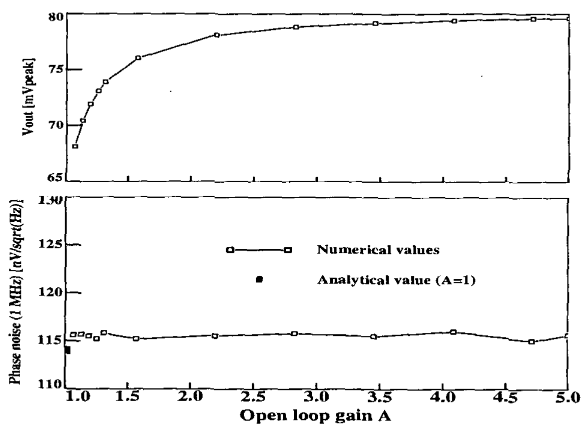

Figure 2. Carrier and phase noise versus open loop gain A.

4. BENCHMARKING USING ODE

Table 1. Oscillator key parameters.

Ref.	CNR_{design}	f_o	f_m	P_{DC}	Q_u
	[dBc/Hz]	GHz	MHz	mW	
[3]	106	3.6	2	1	13.4
[4]	116	6	1	22	7.5
[5]	85	0.9	0.1	30	5
[6]	106	4	1	12	3
[7]	102	1.55	0.1	21.6	7.6
[8]	90	4.7	0.1	10.8	2.4
[9]	136	2	4.7	32.4	3.3
[10]	115	9.8	1	11.6	3
[11]	98.4	6.29	1	18	4

In order to demonstrate the newly defined FOM ODE, the results of recent publications are compared using FOM_2 in equation 2 and using ODE (equation 3). Note that the list of oscillator designs is not exhaustive and that those oscillators are selected of which all the (for ODE) necessary parameters where published. Table 1 list all oscillator parameters of the selected publications. Unloaded quality-factor Q_u is the combination of varactor and inductor quality-factors. Figure 3 shows benchmarking results of the oscillators in table 1 using FOM_2. Oscillator designs are ranked using this figure, but no additional information is included and resonator technology has not been taken into account.

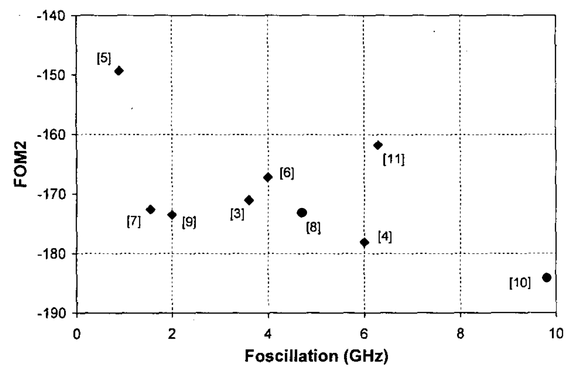

Figure 3. Conventional CNR benchmarking.

Benchmarking of oscillators using ODE is presented in figure 4. ODE shows that the designs from [3, 5] have substantial room for improvement compared to the designs with 1 to 10% design efficiency.

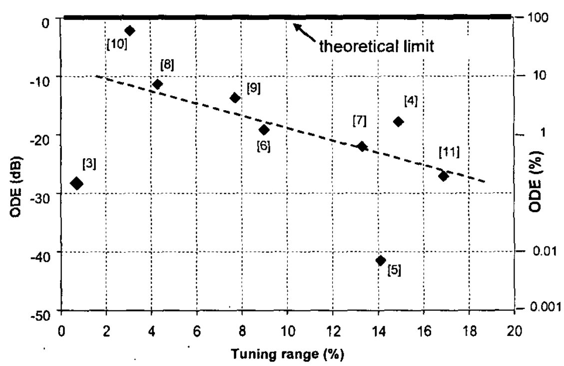

Figure 4. CNR benchmarking making use of ODE.

The trend-line in figure 4 indicates that it is more difficult to approach 100% ODE if the tuning range of the oscillator design is large. Varactors in LC oscillators enable tuning but have a negative influence on the CNR. Fixed capacitances are generally easier to realize with good quality factors than varactors. Furthermore, the varactor is modulated by the noise sources present in the oscillator circuit thus reducing the CNR. In LC oscillators a non-tapped varactor yields maximal tuning range. Capacitive tapping of the varactor results in less tuning range but better overall resonator quality. Since the degree of tapping of the varactor is usually omitted in literature, tuning range is not included in the ODE it self.

Design [10] with 60% ODE is inconsistent. Because the reported DC to RF power conversion efficiency is 15% [10], ODE must be less than 15%. This demonstrates how the built-in consistency check in ODE assists the designer. The designer is alerted to reasses oscillator key parameters when the theoretical ODE limit of 100% is crossed. The in-house oscillator design [3] realized in Silicon on Anything (SOA) [2, 3], features high quality coils and varactors for which ODE normalizes. The relatively low ODE was traced back to a noisy on-chip band-gap reference which biased the VCO. ODE indicates that a significant improvement in efficiency can be expected with improved biasing circuitry.

5. CONCLUSIONS

A powerful new figure of merit for benchmarking CNR of oscillators has been defined, called ODE. It takes into account power dissipation, frequency and resonator technology, allowing absolute comparison of designs. Furthermore, it helps the designer because it indicates the room for improvement. Finally, ODE provides a consistency check. Whenever more than 100% ODE is achieved, oscillator key-parameters should be checked.

6. REFERENCES

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A. DERIVATION OF CNR LIMIT

In order to define the theoretical CNR limit for LC oscillators unambiguously, the LC oscillator will be modeled as shown in 5. The amplifier represents the limiting case of a practical amplifier: i.e. the noise figure F is assumed **0** dB, the input impedance infinite and the output impedance is zero. Final results presented in this appendix are valid both for oscillators using series or parallel resonance.

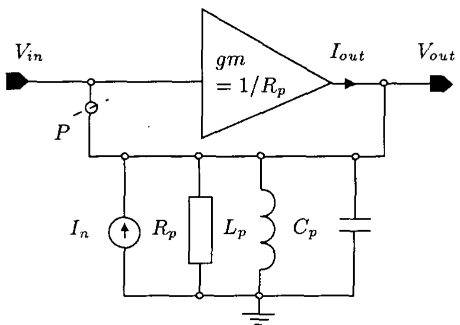

Figure 5. The used oscillator model. The open loop (loop cut open at P) transfer function is given by $gmZ_p(j\omega)$.

For the parallel circuit of R_p, L_p and C_p we can write:

$$Z_p(j\omega) = \frac{R_p}{1 + jvQ_p} \tag{5}$$

with

$$v = \frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \tag{6}$$

$$Q_p = R_p\sqrt{\frac{C_p}{L_p}} = \frac{R_p}{\omega L_p} \tag{7}$$

Using equation 5 we can derive for $H(j\omega)$ of figure 5:

$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)} = \frac{gmZ_p(j\omega)}{1 - gmZ_p(j\omega)} \tag{8}$$

Substituting equation 5 in equation 8, we can write:

$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)} = \frac{gmR_p}{1 + jvQ_p - gmR_p} \tag{9}$$

Assuming we are only interested in the behavior of the oscillator near the oscillation frequency ω_o, a simpler expression for v can be derived. If $|\Delta\omega| \ll \omega_o$, v simplifies to $(2\Delta f)/f_o$.

In order for figure 5 to be an oscillator, the phase and gain condition (Barkhausen) for oscillation have to be met. Using the gain condition ($gmR_p = 1$) and $v = (2\Delta f)/f_o$, $|H(j(f + \Delta f)|$ can be simplified to:

$$\left|\frac{V_{out}(j(f + \Delta f))}{V_{in}(j(f + \Delta f))}\right| = \frac{1}{\frac{2\Delta f}{f_o} Q_p} \tag{10}$$

In the oscillator model the only noise source is R_p. The noise current produced by the resistor is:

$$I_n = \sqrt{\frac{4kTB}{R_p}} \tag{11}$$

Since $gm = 1/R_p$ and $I_{out} = gm * V_{in}$ the noise current can be transferred to the input and hence for V_{in} can be written:

$$V_{in}(j(f + \Delta f)) = \sqrt{4kTR_pB} \tag{12}$$

Combining and squaring equation 10 and 12 and if B is taken 1 Hz, equation 13 can be derived.

$$|V_{out}(j(f + \Delta f))|^2 = \frac{1}{\left(\frac{2\Delta f}{f_o}\right)^2 Q_p^2} 4kTR_p \tag{13}$$

With $V_{carrier-rms}$ being the RMS voltage across the resonance circuit, the power is defined as follows.

$$P = \frac{V^2_{carrier-rms}}{R_p} \tag{14}$$

Combining the previous results leads to equation 15 in which Δf has been replaced by f_m since f_m is more commonly used in literature for the offset frequency from the carrier.

$$\frac{N_o}{P} = \frac{|V_{out}(j(f + fm))|^2}{V^2_{carrier-rms}} = \frac{kT}{P}\frac{1}{Q_p^2}\left(\frac{f_o}{f_m}\right)^2 \tag{15}$$

Here N_o is the total (Single Side Band: SSB) noise power in 1 Hz at fm offset from the carrier [13]. Since half of the noise power will be converted into AM sidebands and half of the noise power into PM sidebands we arrive at the equation for $\mathcal{L}(f_m)$.

$$\mathcal{L}(f_m) = \frac{N_p}{P} = \frac{kT}{2P}\frac{1}{Q_p^2}\left(\frac{f_o}{f_m}\right)^2 \tag{16}$$

Here N_p is the (SSB) phase noise power in 1 Hz at fm offset from the carrier. The CNR of the oscillator can be calculated by taking the $-10\log$ of $\mathcal{L}(f_m)$. As can be expected, results check with [12]. Before CNR_{limit} can be defined for use in the newly defined figure of merit ODE, quality factor Q_p and carrier power P have to be addressed.

Most often unloaded quality factors and DC power dissipation of the VCO are reported instead of loaded quality factor and carrier power, respectively. Since both unloaded quality (Q_u) and DC power dissipation (P_{DC}) represented the best case value of parameters Q_p and P, they qualify best to be used in the theoretical CNR limit CNR_{limit} (equation 4).