

On-Chip Quantization- and Correlation-Robust Jitter Measurement for Low Phase Noise and High Frequency Oscillators

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Abstract—For on-chip oscillator phase noise characterization and monitoring a common technique is the measurement of the equivalent cycle-to-cycle jitter. In this brief we show that the quantization introduced to the recorded jitter by the measurement with a time-to-digital converter can be prohibitive for calculating the phase noise, especially at high oscillation frequencies and for spectrally pure oscillators. A second drawback of this method is that supply voltage noise can mask the phase noise due to intrinsic device noise. To avoid these limitations, we investigate an approach where the oscillator under test is compared to an identical replica. The resulting time difference measurements are introduced as delta jitter. The validity of the method is proven in simulation and measurement of an on-chip jitter measurement macro designed in 16 nm FinFET CMOS technology. The measurement results indicate both robustness against quantization error and a self-canceling of correlated influences on phase noise in delta jitter measurements.

Index Terms—Phase noise, jitter, on-chip measurement, quantization error, time-to-digital converter, device noise.

I. INTRODUCTION

WITH the advancement of CMOS technology enabling various emerging applications (e.g., increased bandwidth communication [1] or quantum computing [2]) the phase noise specifications for frequency sources tighten. Simultaneously due to the continued scaling of semiconductor devices, the statistical variance of noise properties increases. Internal noise sources strongly depend on device architecture, materials and manufacturing. In flicker noise, for example, process variations in the trap density can cause the noise level to vary over orders of magnitude [3]. Hence, additionally to a thorough understanding of flicker noise upconversion in oscillatory circuits [4], [5], [6], careful assessment of the fundamental intrinsic device noise sources is essential for production monitoring, circuit analysis and technology selection

(especially in light of the trend to disaggregated systems adding more freedom to the technology selection [7]).

Oscillator phase noise measurements can replace complex and time consuming device voltage or current noise measurements for monitoring and assessment purposes. The upconverted phase noise of intrinsic sources can however be overshadowed by phase noise due to variations in the supply voltage [8]. We will present an on chip phase noise characterization concept, which allows to measure phase noise without the contribution of supply voltage variation, allowing fast collection of statistically relevant data in production environment or in-field, without the need for a sophisticated lab environment. This enables also self-test applications to monitor temperature or aging effects.

A large variety of on-chip phase noise measurement macros have been proposed. These either use the phase-discriminator method for direct measurements in frequency domain [9] or measure phase deviations in time domain in the form of jitter. In the latter case either the statistical distribution of jitter [10], [11] or its evolution as a function of time is determined with different time-to-digital converters (TDCs) [12], [13], [14], [15]. Independent of the specific implementation, the oscillation always needs to be compared to a reference. Current approaches use either a stable reference source, which cannot be implemented on-chip, or a delay-line to compare the oscillation to a delayed version of itself. For both approaches a separation of the intrinsically caused phase noise is not possible. Additionally, accuracy can suffer for the latter approach due to quantization errors of the TDCs, especially for high oscillation frequencies and low phase noise.

Taking into account the above mentioned arguments and limitations we propose an on-chip phase noise measurement approach, where the reference against which the oscillator under test is compared is a second identical replica (Section II). In Section III we show in simulation that the resulting measurements achieve quantization-robust measurements without the need of a stable reference. The test chip measurements shown in Section IV validate this effect and additionally show the decoupling of intrinsic noise from supply voltage variations.

II. MEASURING PHASE NOISE IN THE TIME DOMAIN

Different physical processes cause nonideal current-voltage behavior in integrated devices, leading to random phase fluctuations $\phi(t)$ in oscillatory systems. Phase noise $\mathcal{L}(f)$ is

defined as a quantity in frequency domain relating to the phase's power spectral density: $\mathcal{L}(f) = \frac{1}{2}S_\phi(f)$, where f , here and throughout this brief denotes the frequency component of the spectrum. The typical phase noise spectrum according to Leeson [16] falls off towards higher offset-frequencies with a $1/f^2$ -dependence before settling to a constant noise floor. The upconversion of flicker noise furthermore produces a $1/f^3$ -dependence for low offset-frequencies.

In time domain these effects can be observed as time shifts of the oscillation edges, quantified by the jitter $\tau(t)$. Depending on the reference used to determine these shifts, different types of jitter can be defined. In the following section we summarize the jitter definitions commonly used and introduce the definition of the delta jitter as a comparison between two independent oscillators.

A. Time-Interval-Error Jitter

By comparing the shifted oscillation edges against their ideal position the time-interval-error (TIE) jitter is determined. In measurement this is only possible if the oscillation can be compared to a stable reference source. The power spectral density of the TIE jitter, denoted by S_τ^{TIE} , can be directly related to the power spectral density of phase fluctuations S_ϕ for an oscillation with frequency f_0 [17]:

$$S_\tau^{TIE}(f) = \frac{1}{4\pi^2 f_0^2} S_\phi(f). \quad (1)$$

B. Cycle-to-Cycle Jitter and N-Cycle Jitter

When the oscillation edge positions are compared against their respective previous edges, the cycle-to-cycle jitter is determined. This quantity is measured with the delay line method by comparing the signal to a delayed version of itself. Here, the effects of low frequency phase variations do not accumulate over multiple periods as in TIE jitter. The scaling relation between the jitter spectrum S_τ^{cycle} and the spectrum of phase deviation S_ϕ therefore shows a dependency on the observed phase noise frequency component f [18]:

$$S_\tau^{cycle}(f) = \frac{\sin^2(\pi f / f_0)}{(\pi f_0)^2} S_\phi(f). \quad (2)$$

This concept can be generalized to time difference measurements between an oscillation edge and the N th previous edge [19]. The obtained N-cycle jitter spectrum can however only be determined in a limited frequency range, since frequencies close to zeros of the \sin -function (f_0/N and its multiples) are highly attenuated in the spectrum.

C. Delta Jitter

In the method investigated in this brief, the oscillator under test is compared against a second identical oscillator. The "delta-jitter" measured is therefore the time difference between the positive edges of both oscillators. Under the condition that the noise caused by their devices is uncorrelated, the power spectral densities of both oscillators' phase functions are additive. Assuming both oscillators have comparable phase noise ($S_\phi^1(f) = S_\phi^2(f) = S_\phi(f)$) leads to the following relation

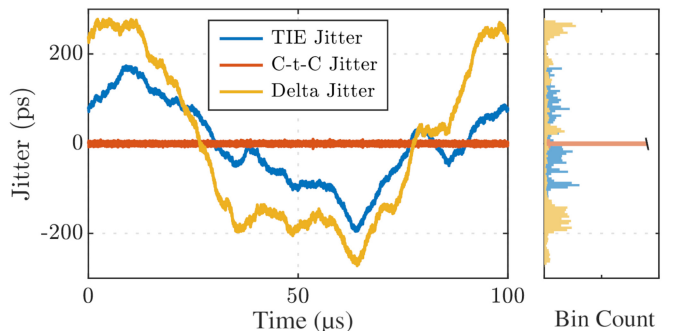


Fig. 1. Evolution of different jitter types with time (left) and their corresponding binning (right). In the histogram of the cycle-to-cycle jitter the two center bins of the histogram are capped.

between the power spectral density of the delta-jitter S_τ^Δ and the spectrum of oscillator phase deviation S_ϕ :

$$S_\tau^\Delta(f) = \frac{S_\phi^1(f) + S_\phi^2(f)}{4\pi^2 f_0^2} = \frac{1}{2\pi^2 f_0^2} S_\phi(f). \quad (3)$$

Correlated effects on the other hand, such as temperature or supply voltage variations on a time scale much larger than the oscillation period affect both oscillators equally and are therefore self-canceling in the measurement of the delta jitter.

III. SIMULATION OF JITTER QUANTIZATION EFFECTS

To investigate possible differences in quantization effects for the various jitter types introduced in Section II, we analyzed a synthetic noisy oscillatory waveform based on the definitions (1) to (3) using MATLAB. For this purpose, we first generated a noisy phase function with white, Gaussian characteristics using the *wgn*-function. For this function subsequently a Fourier transform was employed, and the frequency components scaled according to the phase noise characteristics expected for differential ring oscillators [20], [21], [22] ($\mathcal{L}(1\text{MHz}) \approx -90\text{dBc/Hz}$, with a flicker noise corner of 500 MHz). After transforming the phase function back to time-domain (*ifft*) it is used to generate a noisy oscillatory waveform. Therefor an ideal ring oscillator waveform with frequency of 700 MHz consisting of 21 harmonics is evaluated at the respectively phase-shifted points in time. For the delta jitter a second uncorrelated waveform with identical statistical properties was produced. Subsequently the positive edge-positions were determined and from these the different jitter types. The jitter values were then discretized into bins, as it would happen when measured with an on-chip time-to-digital converter (TDC). Here, a bin width of 5 ps was chosen, in accordance with expected results for the propagation delay of an inverter in current technologies.

Fig. 1 (left) shows the evolution of the different jitter types over the simulated time of 100 μs with their respective mean values subtracted. It can be observed that both TIE jitter and delta jitter wander over a wider range of values, since in their corresponding spectra the low frequency components are dominant. The range of delta jitter values can be observed to be roughly twice as large compared to the TIE jitter. This is the case since here not only the oscillator under test, but also the

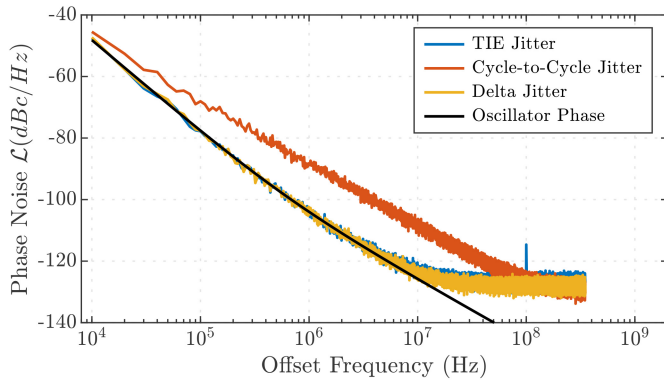


Fig. 2. Phase noise calculated from the different jitter types after quantization.

reference oscillation is subject to phase noise. The cycle-to-cycle jitter on the other hand is limited to a very narrow value band, several picoseconds around zero, which is caused by the suppression of low frequency components.

The quantization of the time series is plotted in Fig. 1 (right). For the TIE and delta jitter the range of values is large compared to the bin width and many different bins are activated. In contrast to that, the cycle-to-cycle (C-t-C) values extend only over the range of four TDC bins, indicating that quantization effects might have stronger impact.

From this time series data the spectrum was calculated via a fast Fourier transform. These jitter spectra were then related to the phase deviation spectrum via (1), (2) and (3), respectively. To reduce the variance of the calculated spectra, which is inherent to the spectrum estimation from data at discrete time steps, the average of several runs was calculated.

Fig. 2 shows the calculated phase deviation spectra. In black color the spectrum of the initial MATLAB-generated phase deviation is shown. Since measuring the jitter is equivalent to sampling the phase deviations with the frequency of oscillation, aliasing of the frequencies higher than f_0 is expected. This behavior is reflected in the spectrum calculated from the TIE jitter: For low offset frequencies the spectrum fits to the oscillator phase spectrum very well, whereas a predictable deviation is observed when approaching the oscillation frequency. In the spectrum of the cycle-to-cycle jitter the effects of quantization are clearly visible: An offset to the expected spectrum is observed over almost the entire frequency range. The spectrum calculated from the delta jitter on the other hand is able to reproduce the phase deviation spectrum as accurately as the TIE jitter.

In further simulations it was observed that the quantization effects have a larger impact on the calculated phase noise spectrum for oscillators with lower phase noise (like typical LC oscillators) or higher frequency. In the first case the phase deviations, and hence the jitter values, are smaller and therefore affected more by quantization. In the second case the same effects are observed since the phase deviations have less time to evolve between subsequent edges.

While a higher TDC resolution (e.g., by Sigma-Delta TDCs) or longer delay in the cycle-to-cycle jitter measurement (N-cycle jitter) can counteract the quantization effects arising with more spectrally pure and faster oscillators, these limitations are not solved in principle.

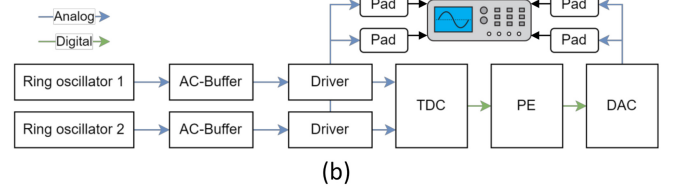
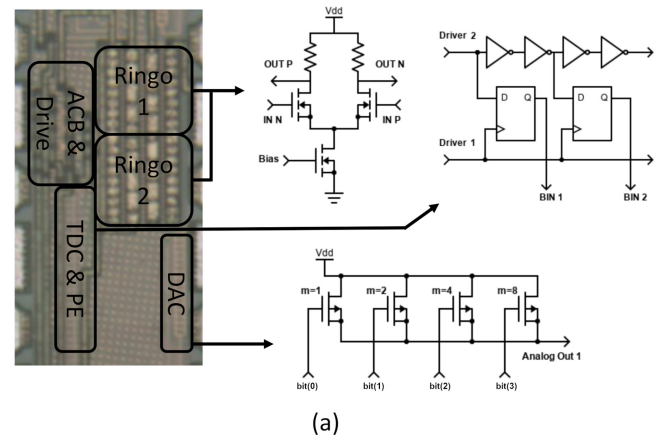


Fig. 3. (a) Micrograph of chip with schematics of ring oscillator delay element, first two bins of the TDC, and DAC. (b) Overview of circuit.

IV. IMPLEMENTATION OF A TEST CIRCUIT

The robustness of the delta jitter method against quantization and its handling of correlated noise sources is investigated with a test circuit, which was designed and measured in a 16 nm FinFET CMOS technology. With the implemented circuit it is possible to measure the phase noise of both oscillators individually with high-accuracy off-chip laboratory equipment, and in addition to that, the delta jitter with an on-chip jitter measurement macro using a TDC. An overview of the complete system with schematics of selected sub-systems is shown in Fig. 3.

A. Design of the Test Circuit

The first components of the test circuit are the two ring oscillators of which the phase noise is to be measured. These consist of 17 differential inverter stages. While both oscillators share the same supply voltage net, their frequency can be tuned separately to allow for corrections of different oscillation frequencies due to process variations. This is realized with a bias voltage controlling the current through the differential stages. According to the simulation of the extracted layout the outputs of the two ring oscillators are oscillating between 450 mV and 800 mV with a frequency of 0.7 GHz.

These signals are then processed by two AC-buffers (ACBs) to produce a rail-to-rail signal between 0 V and 0.8 V suitable for the following digital logic. Since these stages consist of comparatively small transistors to enable fast switching, the drive strength of the signal has to be amplified by subsequent drivers. These consist of seven inverter stages with increasing transistor sizes, additionally splitting the signal into two paths: One for off-chip phase noise measurement via the RF-pads and one for the on-chip jitter measurement.

The measurement of delta jitter between both oscillators is realized with a flash TDC. It consists of 256 flip-flops that are

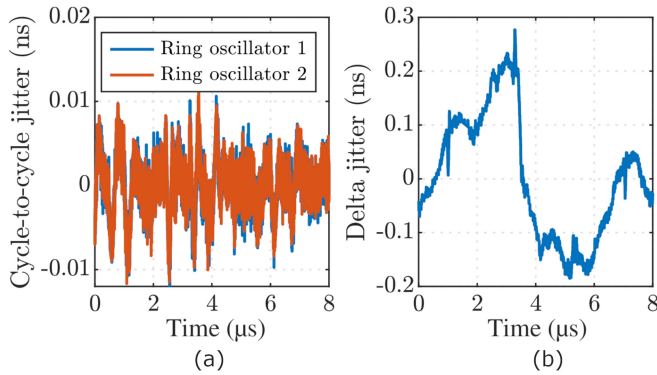


Fig. 4. (a) Cycle-to-cycle jitter of both ring oscillators. (b) Delta-jitter from TDC output.

triggered by the first oscillator. The signal of the second oscillator is connected to the flip-flop inputs via an inverter chain that delays the signal by a specific amount of time between the single stages. Therefore, each time the TDC triggers a snapshot of the second oscillator's past is stored in the 256 flip-flops from which the edge positions can be detected. The quantization is determined by the delay between two neighboring stages and has been simulated to be 5.1 ps for the employed architecture. Since the snapshot of the TDC covers a time longer than one oscillation period, it will contain multiple positive oscillation edges. The next stage, the priority encoder, ignores all recorded edges except the most recent and encodes its position as an 8-bit binary number.

To retrieve this information and make it available for off-chip processing a digital-analog-converter (DAC) is used. It takes the binary number provided by the priority encoder and converts it into a combination of two voltage levels that can be read out at the second pair of RF-pads. In a complete on-chip implementation the DAC would be replaced by digital logic directly processing the priority encoder's output.

B. Measurement of the Test Circuit

To compare the characteristics of the different jitter types, both cycle-to-cycle and delta jitter were measured on the test circuit simultaneously. Wafer level probing (see Fig. 3b) was done with RF probes for the driver and DAC outputs, and DC probes for v_{dd} and bias currents. To compensate for process variations, the frequency of both ring oscillators was matched as closely as possible by adjusting the bias current in the delay cells. The *Agilent Infiniium 92004Q* RF real-time oscilloscope was used to capture driver and DAC output waveform for a measurement time of 8 μ s with a sampling rate of 80 GS/s.

From the recorded data, the cycle-to-cycle jitter for both oscillators was determined: First, the edge positions were calculated by interpolating the time points of threshold crossing. The cycle-to-cycle jitter was then calculated as the time difference between subsequent edges. The evolution of both oscillators' cycle-to-cycle jitter is shown in Fig. 4a. Their apparent correlation is caused mainly by variations in the supply voltage.

The on-chip TDC-recorded delta jitter was obtained from the output waveform of the DAC by mapping the voltage levels

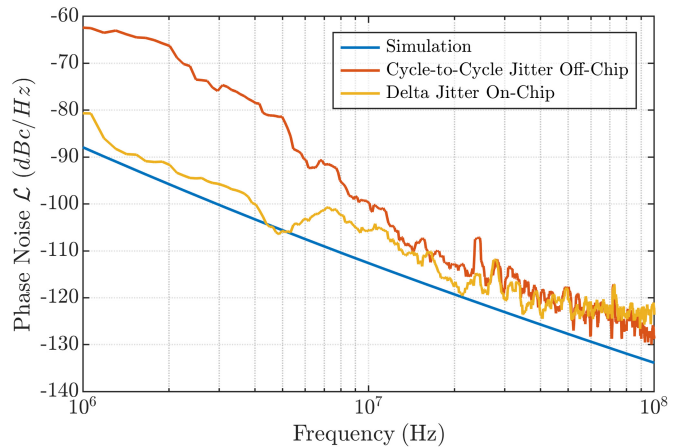


Fig. 5. Comparison of the phase noise spectrum calculated from the cycle-to-cycle jitter of one single ring oscillator and from the delta jitter measured by the TDC with respect to simulation.

to their corresponding TDC bin. Data obtained from a stand-alone TDC characterization was used to determine the delta jitter for each bin. The remaining small frequency difference during the observation window results in a linear shift, which was subtracted in post processing before spectral analysis. The resulting delta jitter is shown in Fig. 4b. The correlated effects seen in the cycle-to-cycle jitter are canceled out and are not observed in the evolution of the recorded delta jitter values, which now depends solely on uncorrelated effects.

From the time series data the phase noise spectra were then calculated. For a clear comparison the off-chip recorded cycle-to-cycle jitter was also quantized to 5 picosecond bins. The resulting cycle-to-cycle jitter of one ring oscillator and the delta jitter were then converted to a phase noise spectrum via (2) and (3), respectively. Since both of these spectra were computed from a finite set of measurement points the resulting periodograms are smoothed in frequency domain to reduce the variance of the estimates. While in principle the proposed method works for arbitrarily low offset frequencies, a limit is set in the current setup by the memory depth of the oscilloscope. The resulting frequency range is especially interesting for broadband applications, like wireless transceivers, where the far-out phase error can limit the performance [19].

Fig. 5 shows the measured spectra, as well as the result of a *spectre* phase noise circuit simulation. For frequency components above 10 MHz good agreement can be observed. On the lower end of the frequency range however, the phase noise as calculated by the delta jitter method is considerably smaller. This is due to the fact that correlated disturbances between both oscillators do not appear in the spectrum due to self-cancellation. The delta-jitter measurement results show the phase noise spectrum caused by the uncorrelated device noise, and therefore match more closely to the simulation.

Furthermore, the results of the simulation in Section III are confirmed when comparing the measured cycle-to-cycle jitter range to that of the delta jitter. As can be observed in Fig. 4, in spite of the rather short measurement time the latter evolves over a time range of several hundred picoseconds, such that the quantization into bin width of approximately 5 picoseconds is negligible for the overall evolution of the delta

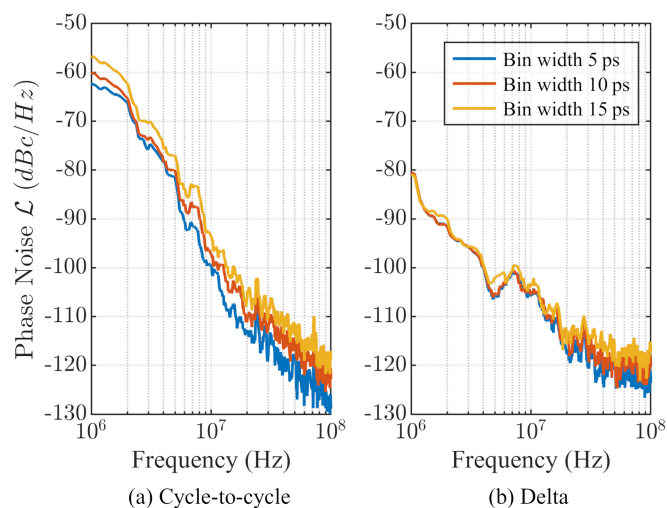


Fig. 6. Quantization effects in phase noise spectra calculated from cycle-to-cycle jitter (a) and delta-jitter (b).

jitter. The cycle-to-cycle jitter on the other hand evolves only over the range of approximately 20 picoseconds, indicating that quantization effects may arise in the spectrum.

A detailed investigation on how the measured phase noise spectra react to quantization is shown in Fig. 6. The TDC resolution is artificially reduced by merging neighbouring bins, resulting in bin widths of 5 ps, 10 ps and 15 ps, respectively. For the cycle-to-cycle jitter (Fig. 6a) an increased bin width causes an offset in the measured phase noise over the entire frequency range (as expected from simulation). While for the delta-jitter (Fig. 6b) an offset is observed for far-out phase noise, the lower frequency components are more robust against quantization and can therefore be measured accurately even with a TDC of lower resolution.

Our measurement and simulation results show that using the delta-jitter concept phase noise due to device noise can be measured decoupled from correlated noise sources. Furthermore it is shown that the method achieves quantization-robust on-chip measurements without a stable reference.

V. CONCLUSION

The simulation of different jitter types shows that for certain combinations of phase noise, oscillation frequency and TDC architecture, the quantization introduced to the measured jitter can prevent a meaningful phase noise measurement. We have therefore designed and fabricated in 16nm CMOS an on-chip circuit, which compares the oscillator under test to an identical replica, enabling quantization-robust jitter measurements without a stable reference source. Furthermore, our test circuit measurements show that the applied method is able to cancel correlated effects, and therefore enables the on-chip monitoring of the phase noise caused by intrinsic device noise.

A drawback of this method is the area overhead needed for the oscillator replica. However, we believe that especially build-in self-monitoring and the recording of a large volume of noise and aging statistics for emerging technologies can immensely benefit from the proposed method by reducing quantization errors, its inertness to supply voltage variations and the ease of direct measurement by on-chip macros.

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