A Phase Noise Measurement System with Frequency Drift Compensation

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Abstract. Commercial equipment provides phase noise measurement solution for voltage-controlled oscillator (VCO), but it also needs to connect additional tuning voltage for VCO frequency stabilization. If the frequency-drifting VCO cannot be tuned directly, the measurement would be difficult. In this article, we present a prototype of a phase noise measurement system, without any connection for frequency stabilization. The innovation of this work is to compensate the frequency drift by introducing a delayed path. The frequency drift of the signal under test is calculated in advance, and then accurately compensates the delayed signal. The results are compared with commercial equipment, and it shows better performance when measuring frequency-drifting signal directly.

1. Introduction

Phase noise is a key parameter for microwave sources which determines the overall performance of system, so characterizing phase noise is important. To measure the phase noise of oscillator accurately, dedicated instruments are usually needed. However, these equipments are not suitable for direct measurement of frequency-drifting signal. For example, the frequency of free-running voltage controlled oscillator (VCO) drifts with time, usually reaches a hundred Hertz/second. Direct measurement of free-running VCO leads to wrong results. Although some equipment such as Keysight 5052B provides VCO measurement solution, additional bias voltage from the equipment needs to control the free-running VCO [1]. Therefore, if the frequency-drifting signal cannot be tuned by voltage, the measurement would be difficult. In this article, we built a phase noise measurement system based on delayed phase locked loop (PLL). This structure is not affected by the frequency drift of the signal under test.

Previous reported methods for measuring the phase noise of frequency-drifting signal include: 1) inject locking the signal under test [2-4]; 2) reference locking [5]; 3) direct measurement [6]. All of them use spectrum analyzer for measurement, which is limited by the reference noise floor of equipment. In comparison, the structure proposed in this article benefits from lower noise floor owing to the cross-correlation between two identical channels.

2. Measuring structure

The signal under test is split into two equal paths and then mixes with reference signals generated by digital to analog converter (DAC), as shown in Fig.1. The frequency of DAC is about 15MHz lower than the signal under test. After a low pass filter, the intermediate frequency (IF) is amplified and sampled in analog to digital converter (ADC). The clock references of DAC and ADC are generated from oven controlled crystal oscillator (OCXO) operating at 100MHz. The ADC is driven at 100MHz directly while the DAC is driven at 6GHz after frequency multiplying.
The sampled signal is sent to FPGA for further calculation. The digital signal from ADC is separated into two paths. The lower path is delayed by $\tau$ while the upper path is sent to a digital PLL. A numerically controlled oscillator (NCO), named as NCO1, is locked to the IF signal. Assume that the input IF signal can be written as:

$$V_{IF} = \cos \left[ 2\pi \left( \bar{f} + f_d \right) t + \phi_1 \right] \quad (f_d = kt) \quad (1)$$

where $\bar{f}$ is the average frequency from 0 to $\tau$, $\phi_1$ is the phase noise of IF signal, $f_d$ is the linear frequency drift with time, the drift slope is $k$. With the use of PLL, the frequency and phase of NCO1 keep the same as the $V_{IF}$. The phase of NCO1 is recorded every period of $\tau$. Another NCO, named as NCO2, is used to repeat these characteristics, including start phase: $\phi(0)$, end phase: $\phi(\tau)$, average frequency $\bar{f}$ and the linear frequency drift $f_d$. Because the phase noise is a zero mean small value, the influence of phase noise on $\phi(\tau)$ can be neglected after long time accumulation. Therefore, the outputs of NCO2 can be expressed as:

$$V_{NCO2} = \cos \left[ 2\pi \left( \bar{f} + f_d \right) t \right] \quad \& \quad \sin \left[ 2\pi \left( \bar{f} + f_d \right) t \right] \quad (2)$$

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Fig. 2. Cancellation of the fixed frequency and the frequency drift from the measured phase. The phase noise with zero mean value remains only.
The delayed IF signal from ADC mixes with NCO2 orthogonally. After passing low-pass filters (LPFs), the orthogonal voltages are:

\[ V_m = \cos[\phi_1] \quad \& \quad \sin[\phi_1] \quad (3) \]

The arctangent calculation demodulated the phase noise \(\phi_1\) of the IF signal, and the mixed signal at zero frequency does not contain frequency drift, as shown in Fig.2. In order not to overflow the phase between 0 and \(2\pi\), a 16 bits register is added ahead of the phase result to extend the range to \(-65536\pi \sim 65534\pi\). Passing through down-sampling cascaded LPFs, the phase noise with different offset range is calculated by cross-correlation between two identical channels. To keep ADCs synchronize between two channels, PLL with 0.1Hz bandwidth is used to lock the OCXOs together.

3. Measurement and results
In our experiment, \(\tau\) is set to 0.33s. Due to the large amount of data, 4Gb DDR3 memory is used for storage. The frequency of DAC is adjusted to preserve 15MHz lower than the signal under test, which is tuned every \(\tau\). The DAC used in this system is AD9162 from Analog Device. A stable microwave signal is measured first and compared with Keysight 5052B. The 5.00172GHz signal to be measured is generated by Keysight E8267D. As shown in Fig.3, the results are nearly the same except for some spurs. To simulate a frequency-drifting signal, we use a free-running VCO for measurement. The VCO used in this experiment is ROS-2150VW+ from Mini-Circuit. To identify the signal under test, the PCB board also contains a 600kHz sinusoidal oscillator. Although the low frequency oscillator is not connected to VCO directly, the output of VCO has 600kHz spur significantly. On average, the center frequency of VCO is 1.01GHz, but it moves left and right dramatically within 1MHz. The measured result is compared with Keysight 5052B, as shown in Fig.4. It is clear that the Keysight 5052B cannot capture the input signal without active frequency control. It produces phase discontinuity at 800kHz, which is incorrect for the measured results. In comparison, this work gets the right result and shows up 600kHz spur. A photograph of this system is shown in Fig.5. Comparison with other works is shown in Table. I. This structure uses two identical paths to suppress noise floor through cross-correlation. Compared with previous works, this structure uses delayed path to compensate frequency drift. Meanwhile, the noise floor of this structure is suppressed by 5*Log(N) by cross-correlation, where N is the correlation times.

| Table I. Comparison with other measurement. |
|-------------------------------------------|
| Frequency drift compensation | This work | [7] | [5] | Keysight5052B |
| Cross-correlation | Yes | No | Yes | Yes (voltage control) |
| Phase noise floor | -130dBc/Hz @10kHz offset (3GHz) | -140dBc/Hz @10kHz offset (10GHz) | -113dBc/Hz @10kHz offset (2.5GHz) | -135dBc/Hz @10kHz offset (3GHz) |

4. Conclusions
In this article, a phase noise measuring system is built. A 1GHz free-running VCO is measured using the proposed structure. This prototype uses digital low-IF structure to subtract phase noise. In FPGA, the signal under test is delayed first. Then its frequency drift is calculated and compensates the delayed signal. The measured results verified that this structure can track frequency-drifting signals without any stabilization control for VCO frequency.
Fig. 3. Phase noise measurement results for signal at 5.00172GHz generated by Keysight E8267D. The signal under test is stable.

Fig. 4. Direct phase noise measurement results of frequency-drifting signal. 600kHz spur is added deliberately to verify the measurement correctness. Direct measurement by Keysight 5052B cannot capture the input signal without active control, while this work could.

Fig. 5. Picture of the proposed phase noise measurement system.
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