A New Measurement Approach for Phase Noise at Close-in Offset Frequencies of Free-running Oscillators

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Abstract—**Measuring the phase noise of low Q free-running oscillators at close-in offset frequencies from carrier (<10KHz) is usually difficult using conventional measurement methods due to the oscillators' frequency instability. To solve this problem, a new measurement technique has been developed as a practical alternative for quick and accurate phase noise measurements without the use of expensive equipment. The injection locking technique is used to stabilize the free-running oscillator with a clean reference source, thus the phase noise can be down-converted and measured by a signal analyzer at base-band. The phase noise of a 9.3 GHz voltage control oscillator (VCO) has been tested to verify the new approach, and the measurement results agree very well with those obtained using an HP phase noise analyzer.**

I. INTRODUCTION

LOW PHASE NOISE OSCILLATORS are in great demand due to the rapid growth in applications of microwave and RF synthesizers. The oscillator's close-in phase noise has become more and more important in improving the overall system performance. In developing high quality and low cost oscillators, one needs to accurately and easily examine the close-in phase noise of oscillators without using expensive equipment. This paper presents a new measurement approach which satisfies this demand.

There are three conventional methods for phase noise measurement: 1) using a spectrum analyzer to measure the power spectrum; 2) using a delay-line as a frequency discriminator; 3) down-converting the phase noise using a clean reference source (phase detector method). Each of these measurement methods has its limitation in measuring low Q free-running oscillators due to the high level of frequency instability of the oscillators [1, 2].

This paper presents a measurement approach which is based on the concept of down-converting an oscillator's phase noise using a stable reference source. Instead of using PLL to synchronize the clean source to the oscillation signal, the injection locking technique is used to provide similar synchronization which can be easily realized for free-running oscillators. In addition to a few microwave components, such as an isolator and a coupler, the only specialized equipment needed in the system is a dynamic

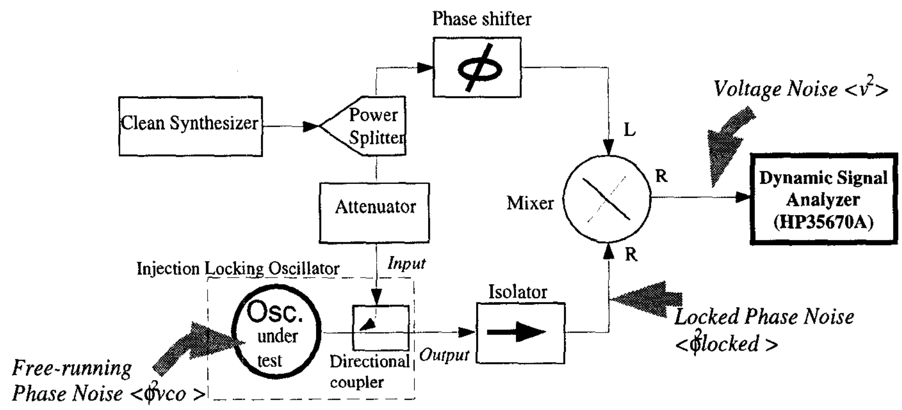

Fig.1 Phase noise measurement setup using injection locking technique.

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signal analyzer.

II. MEASUREMENT SETUP

The proposed phase noise measurement system is shown in the conceptual block diagram in Fig. 1, which is described in detail below:

- A stable synthesizer is used as a reference source, and its output signal is split into two paths. One signal injection locks the oscillator via a directional coupler; the other goes through a phase shifter to a mixer's LO port to be phase compared to the oscillator signal.
- An isolator prevents any signal due to leakage from the LO to RF ports in the mixer from reaching the oscillator; and the phase shifter (or a line-stretcher) is used to setup a quadrature phase difference between the signals at the LO and RF ports allowing the mixer to work as a phase detector.
- The phase noise difference between the reference signal and the injection locked VCO signal is detected by the mixer at the IF port as a voltage noise, $<v^2>$, which is measured by a dynamic signal analyzer.
- The phase noise of the free-running oscillator is retrieved using the measured voltage noise at the dynamic signal analyzer. The detailed theory is presented in the following text.

3. OPERATING PRINCIPLES

In this new approach, injection locking has been chosen to stabilize the oscillator to allow measurements on slowly varying noise. Clearly, the noise measured at the phase detector (the mixer) only presents the phase noise of the locked oscillator, not the free-running one. To retrieve the free-running phase noise, one has to use the relation between the injection locked and the free-running phase noise of the oscillator, which has been well established [3, 4]. The phase noise of a fundamentally injection locked oscillator ($<\phi^2_{locked}>$) can be expressed in terms of the locking bandwidth, phase noise of the reference ($<\phi^2_{ref}>$), and the phase noise of the free-running VCO without any injection locking ($<\phi^2_{vco}>$):

$$<\phi^2_{locked}(\Omega)>=\frac{4\Omega^2<\phi^2_{VCO}(\Omega)>+\Delta\omega^2\cos^2(\Delta\Phi_{inj})<\phi^2_{ref}(\Omega)>}{4\Omega^2+\Delta\omega^2\cos^2(\Delta\Phi_{inj})} \qquad (1)$$

where $\Delta\Phi_{inj}$ is the static phase shift between the locked oscillation signal and the injection signal. $\Delta\omega$ is the injection locking bandwidth of the oscillator, which is defined as the overall frequency tracking range of the injection locked oscillator. Ω is the angular offset frequency for the phase noise power spectrum. When the locked oscillator is phase compared with the reference signal at the mixer, their phase noise difference is detected as voltage noise at the output of the mixer:

$$<v^2(\Omega)>=G_p^2\left\{<(\phi_{locked}-\phi_{ref})^2>\right\}+<\delta v^2>$$
$$=G_p^2\frac{4\Omega^2\left(<\phi^2_{VCO}(\Omega)>+<\phi^2_{ref}(\Omega)>\right)}{4\Omega^2+\Delta\omega^2\cos^2\left(\Delta\Phi_{inj}\right)}+<\delta v^2> \qquad (2)$$

G_p is the phase detection gain of the mixer, and $<\delta v^2>$ represents the noise floor due to the mixer and the signal analyzer (receiver noise). In actual phase noise measurements, the receiver noise floor contribution as well as the phase noise from reference are negligible compared to the noise of the free-running VCO, thus the oscillator phase noise can be directly retrieved from the detected voltage noise using this expression:

$$<\phi^2_{VCO}(\Omega)>=\frac{1}{G_p^2}\frac{4\Omega^2+\Delta\omega^2\cos^2\left(\Delta\Phi_{inj}\right)}{4\Omega^2}<v^2(\Omega)> \qquad (3)$$

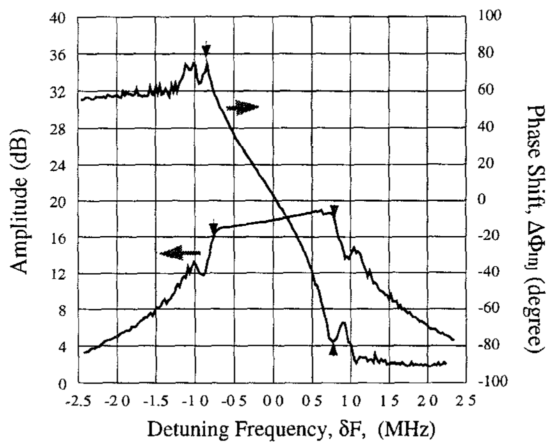

Fig. 2 The transfer function of an injection locked VCO, which is defined as the ratio of the oscillator output to the injection input signal. The detuning frequency is defined as the difference between injection frequency and the original free-running frequency. The free-running frequency of the VCO is 9.3 GHz. The locking bandwidth is about 1.62 MHz, indicated by the two markers.

To conceptually explain the working principles of the above presented theory, the transfer function of an injection locked oscillator is displayed in Fig.2 as a function of the detuning frequency which is defined as the difference between the reference frequency and the intrinsic free-running frequency of the oscillator. Within the locking bandwidth, the amplitude remains flat due to the frequency tracking of the oscillator signal, however, the transfer function phase shift varies approximately from +90° to -90°. This phase shift, $\Delta\Phi_{inj}$, can be expressed as an inverse sin-function of the detuning frequency, δF [5]. Since the phase shift is a strong function of detuning frequency, any frequency jitter in the oscillator will be converted into output phase noise of the locked oscillator. Therefore, an injection locked oscillator can be considered as a frequency discriminator, which converts the oscillator frequency noise into phase noise like a high Q filter or a long delay-line.

By letting $<v^2>$ equal to zero in Eq.2, one will obtain the system noise floor of the whole phase noise measurement system, which is the lowest measurable level of $<\phi^2_{vco}(\Omega)>$:

$$<\phi^2_{floor}(\Omega)>=<\phi^2_{ref}(\Omega)>+\left(\frac{\Delta\omega}{2\Omega}\frac{1}{G_\phi}\right)^2<\delta v^2> \qquad (4)$$

Since the receiver noise contribution is proportional to the inverse of Ω^2, it dominates the noise floor at low offset frequencies, and the effects of reference phase noise will become significant at relatively high offset frequencies. The receiver noise contribution can be easily controlled by adjusting the injection power level, which determines the locking bandwidth. In addition to the noise contribution shown in Eq. 4, there are secondary noise contributions, such as AM/PM noise conversion in the oscillator and the mixer.

4. EXPERIMENTAL VERIFICATION

A BJT based voltage-controlled oscillator (VCO) at 9.3 GHz was used to validate the measurement approach presented in Fig.1. A M/A-COM BJT with 0.25µm emitter-width was used as the active device, and the resonator was realized using lumped LC components. The output power of the VCO was 4dBm, and the injection signal was approximately -35 dBm. An HP8671B synthesizer was used as the reference source, and an HP35670A dynamic signal analyzer was used to detect the down-converted noise signal at base-band from 10Hz to 51 KHz.

In the measurement, the injection frequency of the reference signal was tuned slowly across the free-running frequency to determine the injection locking bandwidth. Meanwhile, the phase detection gain of the mixer was obtained by observing the DC voltage variation at the mixer IF port. The reference frequency was then fixed at the center frequency of the injection locking bandwidth to set $\Delta\Phi_{inj}=0$, and the phase shifter was adjusted to the quadrature phase difference between the LO and RF signals at the mixer. The measured injection locking bandwidth was 1.62MHz, and the phase detection gain of the mixer was 0.102v/radian. The power spectrum of the detected voltage noise measured by the singal analyzer for the 9.3 GHz VCO is displayed in Fig. 3.

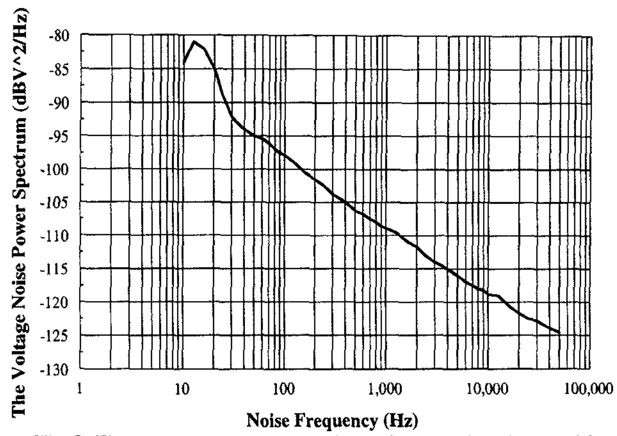

Fig.3 The power spectrum of the voltage noise detected by the dynamic signal analyzer in measuring the 9.3 GHz VCO. The noise floor of the dynamic signal analyzer, $<\delta v^2>$ was approximately -150dBV^2/Hz.

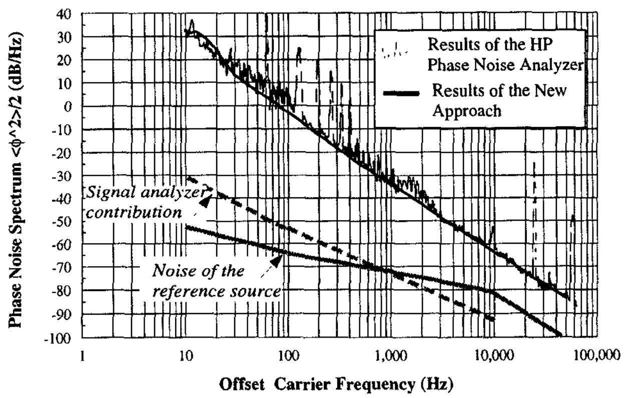

Fig.4 The measuredphase noise of the 9.3 GHz free-running VCO as a function of offset carrier frequency. Notice that the one-half of phase noise power is displayed since the HP analyzer output format was "single-side-band (SSB) signal to noise ratio".

The free-running phase noise of the VCO is then determined using Eq. 3 as shown in Fig.4. The phase noise of the same oscillator measured using an HP phase noise analyzer is also displayed in Fig.4 for comparison. In measuring the VCO's phase noise with the HP phase noise analyzer (HP3047A), the delay-line approach was used due to the difficulty in phase locking the synchronizer to the VCO. The time delay of the delay-line was about 12ns, and the corresponding system noise floor for this phase noise measurement was approximately -75dBc/Hz at 10KHz.

The comparison clearly shows excellent agreement between the two measurement methods. The slight discrepancies between the two measurement results are mainly due to the different environmental noise sources at the two measurement sites. The system noise contributions in the proposed approach are also displayed in Fig. 4. As indicated by Eq. 4, at close-in offset frequencies (<1KHz), the floor is dominated by the noise of the dynamic signal analyzer, which is 30 to 50 dB lower than the noise of the VCO. At frequencies above 1 KHz, the reference phase noise from the stable synthesizer determines the system noise floor.

5. DISCUSSIONS

Being a frequency discriminator realized by injecting a clean reference signal to an oscillator, the new approach can be considered as a compromise between the delay-line method and the phase detector method with PLL [1]. The combination of the advantages of these two methods makes the compromise very suitable for low Q free-running oscillators with injection locking path. For example, a reliable injection locking bandwidth at 1MHz can be easily achieved in the above mentioned 9.3 GHz VCO. To achieve the equivalent level of frequency discrimination, one would need a 500 ns time-delay, or approximately 70 meter low-loss cable, which is impractical. Compared to the phase detector method with PLL, one advantage of using injection locking is that it can be easily realized since the injection locking only needs a few microwave components. One can easily increase the injection locking bandwidth by increasing the injection power to overcome the oscillator's frequency drift, whereas such frequency tracking is very limited in the conventional PLL approach due to the tracking bandwidth of the synthesizer.

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