A New Phase Shifter-less Delay Line Method for Phase Noise Measurement of Microwave Oscillators

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A New Phase Shifter-less Delay Line Method for Phase Noise Measurement of Microwave Oscillators

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Abstract— **In this paper a new method for measuring phase noise of microwave oscillators based on delay line frequency discriminator is proposed. Eliminating of phase shifter is the major advantage of this technique over traditional delay line technique. By using this new technique, we get rid of manually or electronically tuning of phase shifter to reach phase quadrature at the phase detector input ports. A 90-degree Hybrid is used in this technique and another path including phase detector and LNA is added. Finally by using dual channel FFT analyzer and performing some calculation over sampled data of two channels, the phase noise of oscillator will be extracted. A setup based on proposed method was constructed and phase noise of a 3 GHz phase locked oscillator was measured via three methods; traditional delay line method, phase shifter-less method and direct spectrum reading from spectrum analyzer. Comparing the measured data of three methods has shown validity of the proposed method.**

I. INTRODUCTION

Phase noise of oscillator is one of the most important parameters that determine the quality and performance, in the RF and wireless systems. Due to this object, characterizing and measuring phase noise of an oscillator is extremely necessary. There are different techniques for measuring phase noise. We can categorize them to three basic techniques; direct-spectrum, two oscillator method, and single-oscillator method.

Direct-spectrum reading is the easiest method of measuring phase noise. With an oscillator connected directly to a spectrum analyzer, phase noise measurements are made from the spectrum analyzer‘s display. However the phase noise of the spectrum analyzer‘s internal local oscillator limits the dynamic range of the direct spectrum measurement. In addition, errors may be caused by the level of amplitude noise, since a spectrum analyzer does not distinguish amplitude noise from phase noise. Another limitation with this method is that we can not measure a free-running oscillator’s phase noise due to spectrum variation results from frequency instability. This means that only phase noise of very stable or locked oscillators can be measured.

In two-oscillator technique [1] (sometimes called PLL technique), an additional pure oscillator is locked to the oscillator under test. The outputs of two oscillators are applied to a phase detector which is usually a double balanced mixer. Phase detector output which is proportional to the oscillator phase noise is applied to a low noise amplifier. Ultimately, the amplified signal is applied to a spectrometer which is a spectrum analyzer or a digital FFT analyzer. After calibration and attending necessary considerations, we obtain the phase noise of the oscillator. This method has the best sensitivity but for unstable oscillators with regard to PLL bandwidth needs more care and is more complicated. On the other hand this setup is very expensive.

Another classic method for measuring phase noise is FM discriminator method [1, 2] which is usually implemented with a delay line or a high-Q resonator and based on the measurement of frequency fluctuations. In this method, no additional oscillator is required. The output of the oscillator under test is divided into two paths. One path contains a delay line and optionally an amplifier and the other, has a phase shifter. For each measurement, the phase shifter must be adjusted manually or electronically, for phase quadrature at the phase detector input ports. Output of mixer is a fluctuating voltage, analogous to the frequency fluctuations of the oscillator, centered on approximately zero dc volts. Then, mixer output is amplified by a LNA and applied to a spectrum or FFT analyzer. Finally by performing calibration, we get to the phase noise of interest. The major advantages of FM discriminator method over two-oscillator technique are ability of measuring phase noise of unstable oscillators and also easy and cheap to implement. But the phase noise floor of this technique is higher than two-oscillator technique especially in near-carrier offsets.

The methods described above are the most popular methods, used in phase noise measurement. There are some different techniques in the literature. Zhang et al. [3] introduced a new method, which is similar to the PLL method, but it uses injection locking to synchronize the oscillators. Synchronizing the oscillators by injection locking is much simpler than phase-locked looping them. In addition, it is not necessary that one of the oscillators has the electronic tuning capability. Nick et al. [4] introduced a new phase noise measurement method based on inter-injection locking of two similar oscillators. In this method, the average phase noise of two free-running oscillators is measured. By using cross correlation technique, we can improve phase noise floor of measurement system up to 20 dB in the two-oscillator and single oscillator techniques [5] at the expense of using more hardware.

II. MEASUREMENT SETUP AND PROCEDURE

Our proposed method basically belongs to FM discriminator category. It can be implemented either by a high-Q resonator or by a delay line. As we can reach to a wideband phase noise measurement system with delay line discriminator, we developed our theory and equations with regard to delay line. The major advantage of proposed technique over traditional delay line technique is elimination of phase shifter which is used for making phase quadrature at the phase detector input ports. The block diagram of ordinary method is shown in Fig. 1.

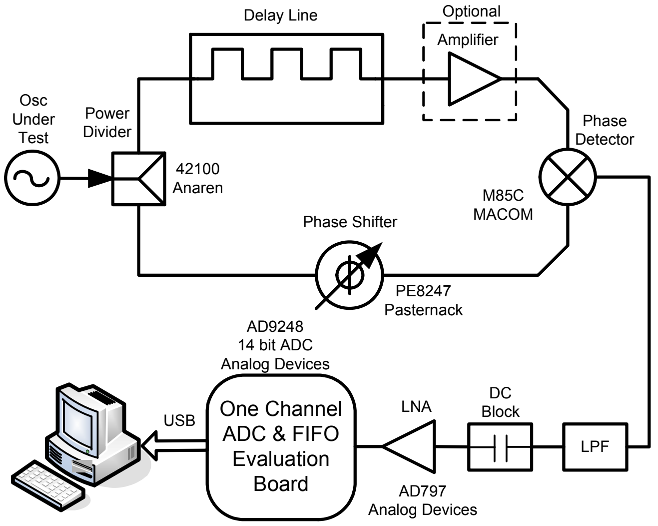

Fig. 1 Ordinary Delay Line Technique for phase noise measurement

In the proposed method, a 90-degree hybrid and another path including a phase detector and a LNA have been added. Then a dual channel synchronized sampling system is required to perform sampling detected signals and necessary processing. In other word, an I/Q phase noise detection is occurred. Fig. 2 shows the block diagram of the proposed method. In the following, we will introduce how one can reach to the phase noise of the oscillator by the proposed method.

For phase noise analysis, it is ordinary assuming phase noise as narrowband FM sidebands around the carrier. So consider the source under test is a modulated FM sinusoid:

$$v_{osc}(t) = A\sin\left(\omega_C t + m\sin(\omega_m t)\right) \tag{1}$$

With regard to Fig. 2, we can proceed and write the signals at each node. For the indicated signal with condition $m << 1$, the ratio of sideband FM level to carrier level is $m/2$.

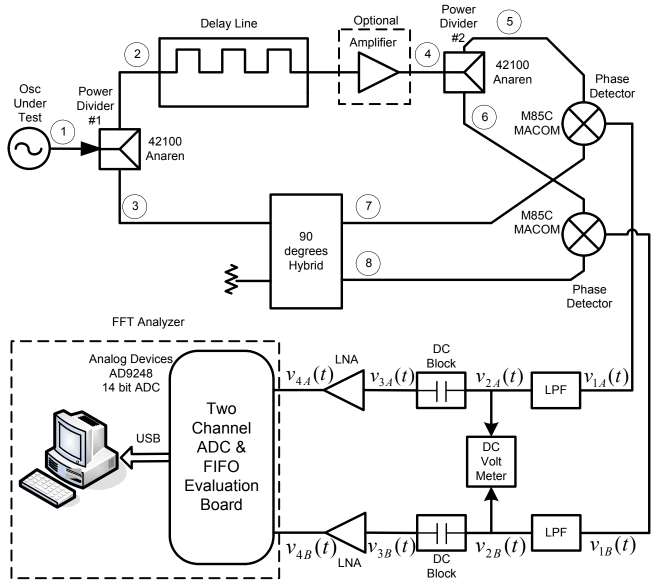

Fig. 2 Proposed phase noise measurement setup.

At nodes 5 and 6, we have;

$$v_5(t) = v_6(t) = \frac{A}{2L_D}\sin\left[\omega_C(t-\tau) + m\sin\left(\omega_m(t-\tau)\right)\right] \tag{2}$$

where L_D and τ are delay line's loss and time delay parameters. For nodes 7 and 8;

$$v_7(t) = \frac{A}{2L_H}\sin\left[\omega_C t + m\sin\left(\omega_m t\right) - \theta_0\right] \tag{3}$$

$$v_8(t) = \frac{A}{2L_H}\sin\left[\omega_C t + m\sin\left(\omega_m t\right) - \frac{\pi}{2} - \theta_0\right] \tag{4}$$

where L_H and θ_0 are hybrid's loss and phase shift at carrier frequency f_C.

The path length between power divider #2 and mixers must be equal. Also path length between hybrid and mixers must be equal too. This is a critical point because we need the mixers fed from power divider #2 in phase, and from the hybrid with quadratic phase. Mixers and all the components following them to dual channel FFT analyzer should have same characteristics. Therefore at the mixers' outputs we have;

$$v_{2A}(t) = \left[x_5(t).x_7(t)\right]_{Low\,Pass} = \frac{A^2}{8L_D L_H}K_\varphi \times \cos\left[\omega_C\tau + m\left(\sin\left(\omega_m t\right) - \sin\left(\omega_m(t-\tau)\right)\right) - \theta_0 + \theta_M\right] \tag{5}$$

$$v_{2B}(t) = \left[x_6(t).x_8(t)\right]_{Low\,Pass} = \frac{A^2}{8L_D L_H}K_\varphi \times \sin\left[\omega_C\tau + m\left(\sin\left(\omega_m t\right) - \sin\left(\omega_m(t-\tau)\right)\right) - \theta_0 + \theta_M\right] \tag{6}$$

where K_φ and θ_M are phase detector coefficient and phase shift at carrier frequency f_C. If we expand (5) and (6) and simplify the results, we will reach to (7) and (8).

$$v_{2A}(t) = k\cos\left[2m\sin(\xi).\cos(\omega_m t - \xi) + \varphi_0\right] \quad (7)$$

$$v_{2B}(t) = k\sin\left[2m\sin(\xi).\cos(\omega_m t - \xi) + \varphi_0\right] \quad (8)$$

we wrote (7) and (8) by the substitution $A^2K_\varphi / 8L_D L_H = k$, $\omega_m\tau/2 = \xi$ and $\omega_C\tau - \theta_0 + \theta_M = \varphi_0$. By expanding (7) and (8), one obtains;

$$\begin{aligned} v_{2A}(t) &= k\cos\left[2m\sin\xi.\cos(\omega_m t + \xi)\right]\cos(\varphi_0) \\ &\quad - k\sin\left[2m\sin\xi.\cos(\omega_m t + \xi)\right]\sin(\varphi_0) \end{aligned} \quad (9)$$

$$\begin{aligned} v_{2B}(t) &= k\sin\left[2m\sin\xi.\cos(\omega_m t + \xi)\right]\cos(\varphi_0) \\ &\quad + k\cos\left[2m\sin\xi.\cos(\omega_m t + \xi)\right]\sin(\varphi_0) \end{aligned} \quad (10)$$

For $\alpha << 1$, we can use approximations $\sin\alpha \approx \alpha$ and $\cos\alpha \approx 1$. Therefore we can simplify (9) and (10) with regard to $\xi = \omega_m\tau/2 << 1$.

$$v_{2A}(t) = k\cos(\varphi_0) - km\omega_m\tau.\cos(\omega_m t + \xi)\sin(\varphi_0) \quad (11)$$

$$v_{2B}(t) = k\sin(\varphi_0) + km\omega_m\tau\cos(\omega_m t + \xi)\cos(\varphi_0) \quad (12)$$

From (11) and (12), consider that there are two terms at the phase detectors output. One term is DC component and the other is the AC or interested FM component. As can be seen, the AC component depends on the constant phase φ_0. In ordinary delay line technique, φ_0 is set to $(2k+1)\pi/2$ by using phase shifter. In the proposed method phase shifter doesn't exist. So for getting rid of φ_0 the DC component of phase detectors' output, is measured by DC volt meters. If DC value of (11) and (12) are shown with A and B, then parameters φ_0 and k will be calculated with solving triangular equations according to (13) and (14).

$$\varphi_0 = \tan^{-1}\left(\frac{B}{A}\right) + (1 - \mathrm{sgn}(A))\frac{\pi}{2} \quad (13)$$

$$k = \frac{A}{\cos(\varphi_0)} \quad (14)$$

We added the second term in (13) in order to determine the φ_0 triangular region with regard to DC values signs, correctly .Since the interested signal level at the phase detector output is very low, it is necessary to be amplified. After eliminating DC components and low noise amplification, detected signals will be applied to a two-channel synchronized sampling system. If we perform a calculation according to (15) on the sampled data, φ_0 will be eliminated.

$$v_{calculated}(t) = A.v_{4B}(t) - B.v_{4A}(t) = k^2 m\omega_m\tau G\cos(\omega_m t + \xi) \quad (15)$$

where G is the LNA voltage gain. It is necessary to perform a calibration factor to reach sideband level $m/2$ and apply to measured amplitudes;

$$CalFactor = \frac{m/2}{k^2 m\omega_m\tau G} = \frac{1}{2k^2\omega_m\tau G} \quad (16)$$

III. Experimental Verification

A. System Description

For evaluating the proposed method, we constructed a setup according to Figure 1. The components and devices were selected to work in the range of 2 to 18 GHz. To have better sensitivity it is necessary that the delay line has minimum loss. Because the more the level at the mixer inputs causes the more phase detector sensitivity. So we used the EZ250 cable from Ezform with 100 feet long to have about 120ns delay and low loss line. Two double balance mixers from MA/COM were used as phase detectors. A low pass filter with 1 MHz cut-off frequency is used in each channel both for cancelling additional mixing products and for limiting bandwidth to prevent aliasing problem. DC component of two phase detectors are sampled by AD1674 (12 bit analog to digital converter) and sent to PC via COM port. To amplify low level detected signals, we used ultra low noise op-amp AD797 from Analog Devices in two stages with 67 dB gain. Similarity of two channels is important to prevent to reduce overall errors. A dual channel 14 bit analog to digital converter evaluation board from Analog Devices was used for sampling and recording data. The clock rate of sampling system is 4.096 MHz and the FIFO length on the evaluation board is 256 kilo Samples. Finally the sampled data is transferred to a PC via USB and the data is processed in MATLAB package to depict phase noise diagram. The setup is shown in Fig. 3.

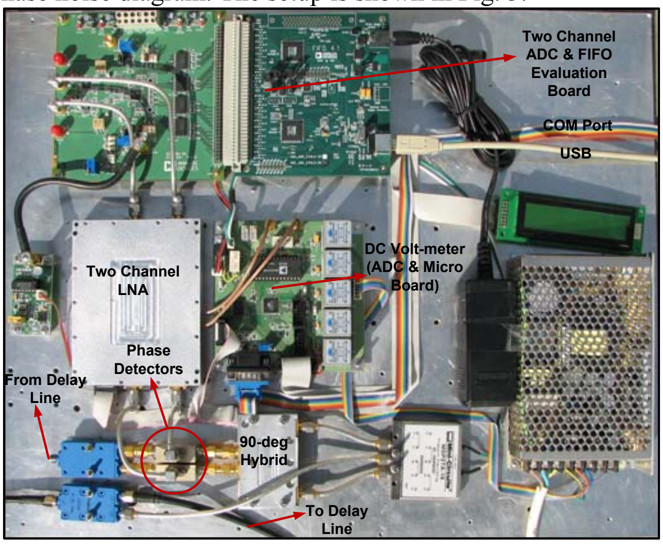

Fig. 3 Image of constructed setup for evaluating proposed method

B. Total Calibration

It is necessary to perform a total calibration on the setup. A straightforward calibration process is applying a FM modulated signal to measurement setup. This signal which is usually made by a signal generator is applied to spectrum analyzer and the side lobe level relative to carrier level is read. Similar level after calculation should be measured at the same offset. So it may be necessary that a constant added (in dB domain) to calculated data.

C. Evaluating the Measurement Results

By the constructed setup, it is possible to measure phase noise of any kind of microwave oscillators, either free-running or phase locked oscillators. Since the spectrum analyzer can measure phase noise of only high stable or phase locked oscillator, we prepared a PLO at 3 GHz in order to compare our method with spectrum analyzer measurement. Also, for comparing our method with ordinary delay line technique, we construct a setup based on ordinary delay line according to components and devices shown in Fig. 1. We used a synthesizer IC with part PE3336 from Peregrine, a VCO with part ROS-3000 from Minicircuits and a 20 MHz reference TCXO with 0.9 ppm stability to construct a relative low phase noise PLO at 3 GHz. We measured phase noise of the PLO by three methods mentioned above and compared the results on a same plot. For each measurement with our method and ordinary delay line method, we performed 100 times measurement with averaging the results to eliminate instantaneous fluctuations. The plot is drawn from 500 Hz to 500 kHz offset and is shown in Fig. 4.

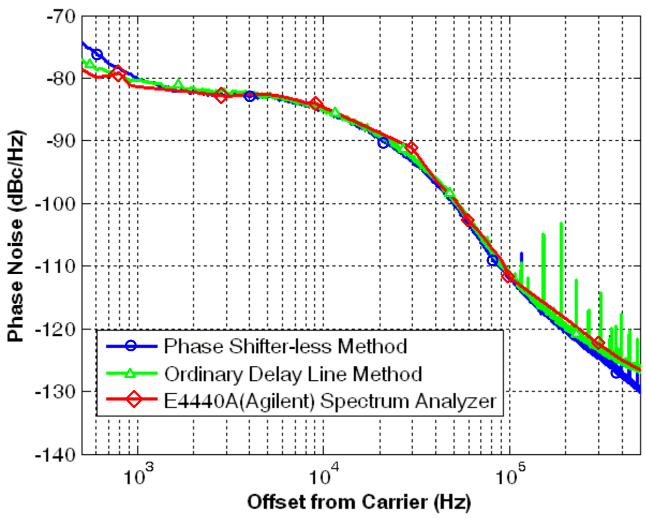

Fig. 4 The result of phase noise measurement of the PLO with three different methods (phase shifter-less method, ordinary delay line method and spectrum analyzer measurement

As shown in Fig. 4, there is very good compatibility between the three measurements.

For near carrier offsets, some difference is seen. All frequency discriminator methods suffer from measuring near carrier offset due to performing calibration factor. The sensitivity of frequency discriminator methods is limited by a factor by $1/f^2$. Because they detect FM noise and then PM noise is extracted. Relation between FM noise and PM noise is [6]:

$$S_\phi(f) = \frac{1}{f^2} S_f(f) \tag{17}$$

One can understand this subject by considering calibration factor shown in (16). Also it is seen that for higher offset above 100 kHz, there is some difference. The reason of this behavior can be understood with regard to approximation we assumed $\xi = \omega_m \tau / 2 << 1$. For higher offsets, this condition is not valid and degrades measurement accuracy.

IV. Conclusion

The proposed setup which is based on frequency discriminator delay line technique measures the phase noise of microwave oscillator precisely. By applying this method, So this set-up can be used in automatic test equipment and there is no need to phase shifter tuning, manually or electronically. Sensitivity of this method is lower than PLL method, but the complexity and cost of this method is lower. Also this method can be used for any types of oscillators whereas it is hard to measure such oscillators with PLL technique. In addition, It is possible to extend the frequency range of phase noise measurement up to millimeter waves with the proposed method.

Acknowledgment

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