Residual PM Noise Evaluation of Radio Frequency Mixers

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***Abstract*—Direct observation of phase-modulation (PM) noise is often difficult due to the high dynamic range that exists between the carrier and the modulated sidebands. A common tool used to reduce the dynamic range is the phase detector, which removes the carrier and down-converts its noise sidebands to baseband. The double balanced mixer (DBM) is the most widely used phase detector for high-resolution PM noise detection at most carrier frequencies. For Fourier offset frequencies close to the carrier, the residual flicker phase noise of the DBM is often the limiting factor of a PM noise measurement system. Careful evaluation of the phase detector under various operating conditions can lead to the optimization of a PM noise measurement system's sensitivity. This paper describes a survey of residual PM noise measurements for a variety of DBMs at 5 MHz. In order to attain quality measurements, careful attention is devoted to the reduction of ground loops during PM noise measurements. The input powers to the local oscillator (LO) and reference frequency (RF) ports of the mixers are varied to determine the optimal operating point of these devices.**

***Index Terms*— Flicker noise, mixers, phase detector, phase noise.**

I. INTRODUCTION

The measurement of close to carrier phase modulation (PM) noise of state-of-the-art oscillators is always challenging [1]. Quite often the residual noise of the phase detector used in these measurements is the source of difficulty [2], in particular, at Fourier offset frequencies below 100 Hz, where oscillator noise has a slope of f^{-3} and may be lower than the mixer noise floor, which follows a slope of f^{-1} [3]. The motivation for this paper is to locate mixers that offer low phase noise at 5 MHz for use in high resolution measurement systems. This paper describes a survey of PM noise measurements for 18 DBMs used as phase detectors [4, 5]. A study of the phase sensitivity of these detectors with operating power is also investigated. The measurement system used to characterize the detectors is described in section II, and the results of this survey are summarized in section III.

*This report summarizes the noise for various mixers by product name for completeness of this survey. No endorsements are implied.

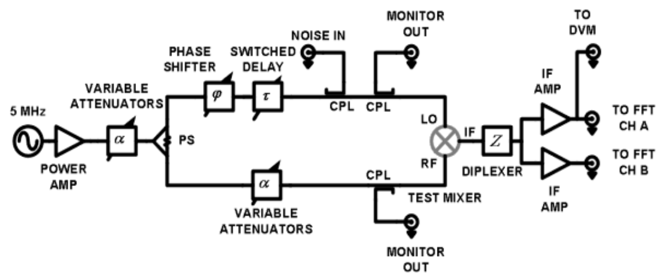

Figure 1. Block diagram of residual PM noise measurement system. PS: power splitter, CPL: directional coupler, IF AMP: low noise baseband amp, DVM: digital voltage meter, FFT: two-channel fast Fourier transform analyzer.

II. DESCRIPTION OF THE MEASUREMENT SYSTEM

The PM noise of the detectors for this survey is measured by use of a 5 MHz cross-correlated homodyne measurement system[6, 7, 8]. Fig. 1 shows a block diagram of the measurement configuration. The signal from a 5 MHz reference oscillator is amplified and split to drive the local oscillator (LO) and reference frequency (RF) ports of the detector. Variable attenuators are used to test the detectors at different power levels. A phase shifter is used to set a 90° quadrature condition between the LO and RF signals. In quadrature, the common-mode phase fluctuations of the oscillator and power amplifier cancel, and the residual noise of the detector is measured. The switched delay line and "Noise In" port are used to calibrate the system's phase sensitivity.

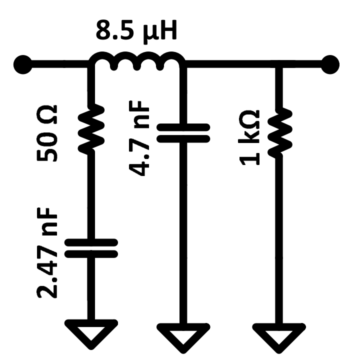

Figure 2. Mixer IF Diplexer schematic.

The detector is followed by a diplexer and a pair of baseband intermediate frequency (IF) amplifiers [9]. The diplexer, shown in Fig. 2, terminates and filters the high-frequency products of the mixing, while still maintaining a high voltage-to-phase conversion at baseband. This diplexer also allows for the baseband signals to be amplified without saturating the IF amplifiers with the 5 MHz and 10 MHz signals from the mixing process. The topology of the diplexer at the output of the phase detector plays a very important role in its performance [10, 5]. The pair of IF amplifiers is utilized to minimize the noise contribution of the fast Fourier transform (FFT) analyzer to the measurement. The uncorrelated input voltage noise of each IF amplifier is reduced by the use of cross-correlation. This allows measurement of the correlated residual detector noise [7]. This noise contribution of the IF amplifiers to the measurement is shown in Fig. 3.

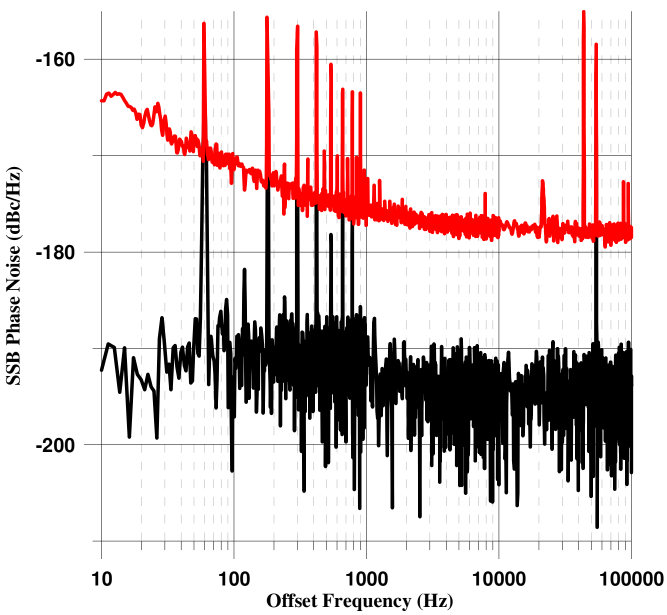

Figure 3 Plot shows that the PM noise of the phase detectors (Top) is higher than the noise floor of the IF amplifiers (Bottom).

In phase quadrature, the filtered output voltage of the detector is represented by

$$v = k_d \cos(\Delta\varphi + \pi/2) \quad (1)$$

where k_d is the mixer sensitivity in volts/rad and $\Delta\varphi$ is the differential phase deviation from quadrature between the LO and RF ports. For small phase deviations, k_d can be determined from a known phase shift introduced by the calibrated delay line. k_d is the ratio of DC voltage change to the introduced phase shift. This method of k_d calibration was also checked against single-sideband modulation and noise-injection methods [11, 12].

III. Measurement Results

For this survey 18 types of phase detectors have been compared. Each mixer was evaluated at two operating points.

1. Linear operation
   LO power = Nominal specified LO power
   RF power = 1 dB below the RF compression point.

2. Saturated operation
   LO power = Maximum mixer power 11 dBm.
   RF power = LO power.

Fig. 4 shows the range of PM noise for the measured devices on two separate plots. Due to the large number of devices evaluated, the measured residual PM noise of the detectors is reported at two offset frequencies; 10 Hz for specifying flicker PM noise and 100 kHz indicating thermal PM noise. The top and bottom plots show the 10 Hz and 100 kHz data respectively for each detector. Each offset frequency is displayed as a line with endpoints representing the linear and saturated measurement values.

Often the PM noise of the phase detectors decreased significantly when they were operated in saturated mode. As discussed in [1, 5], this is attributed mostly to the higher sensitivity, k_d, in saturated operation. For this survey, mixers with a nominal LO rating of +7 dBm and maximum rating of +17 dBm are classified as low-power. Mixers with a nominal LO power rating above +7 dBm are classified as high-power for this study. It can be seen in Fig. 4 that the variation of measured PM noise is greater in high-powered DBMs than for the low-power mixers. Of the commercial detectors, the HP10534A* has the lowest flicker and the ZAD-1H+* the lowest white noise in linear operation. The MCL ZRPD-1+* showed the largest improvement in its white noise between linear and saturated operation, and has the lowest white noise level overall. The PM noise of the best detectors surveyed in saturated mode are presented in fig. 5. The lowest level of flicker noise observed is in a custom mixer built and described in the following section.

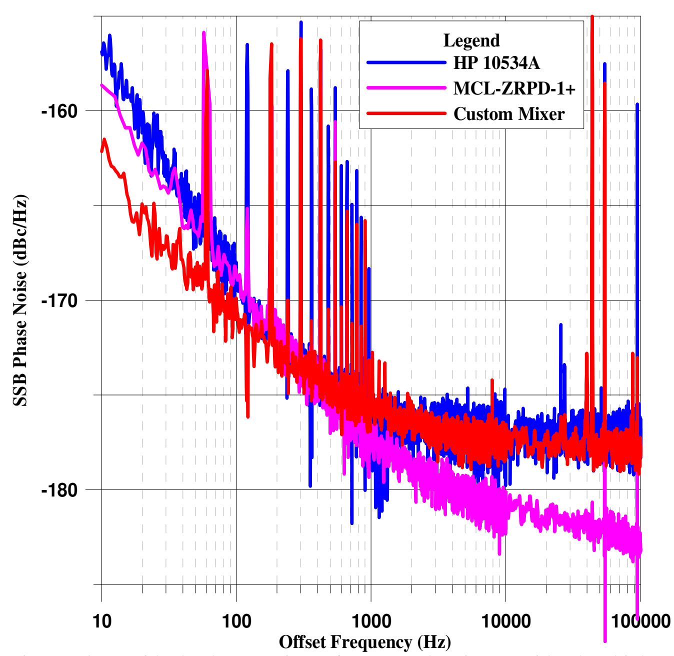

Figure 5. Residual phase noise of surveyed mixers with the highest performance in saturated operation.

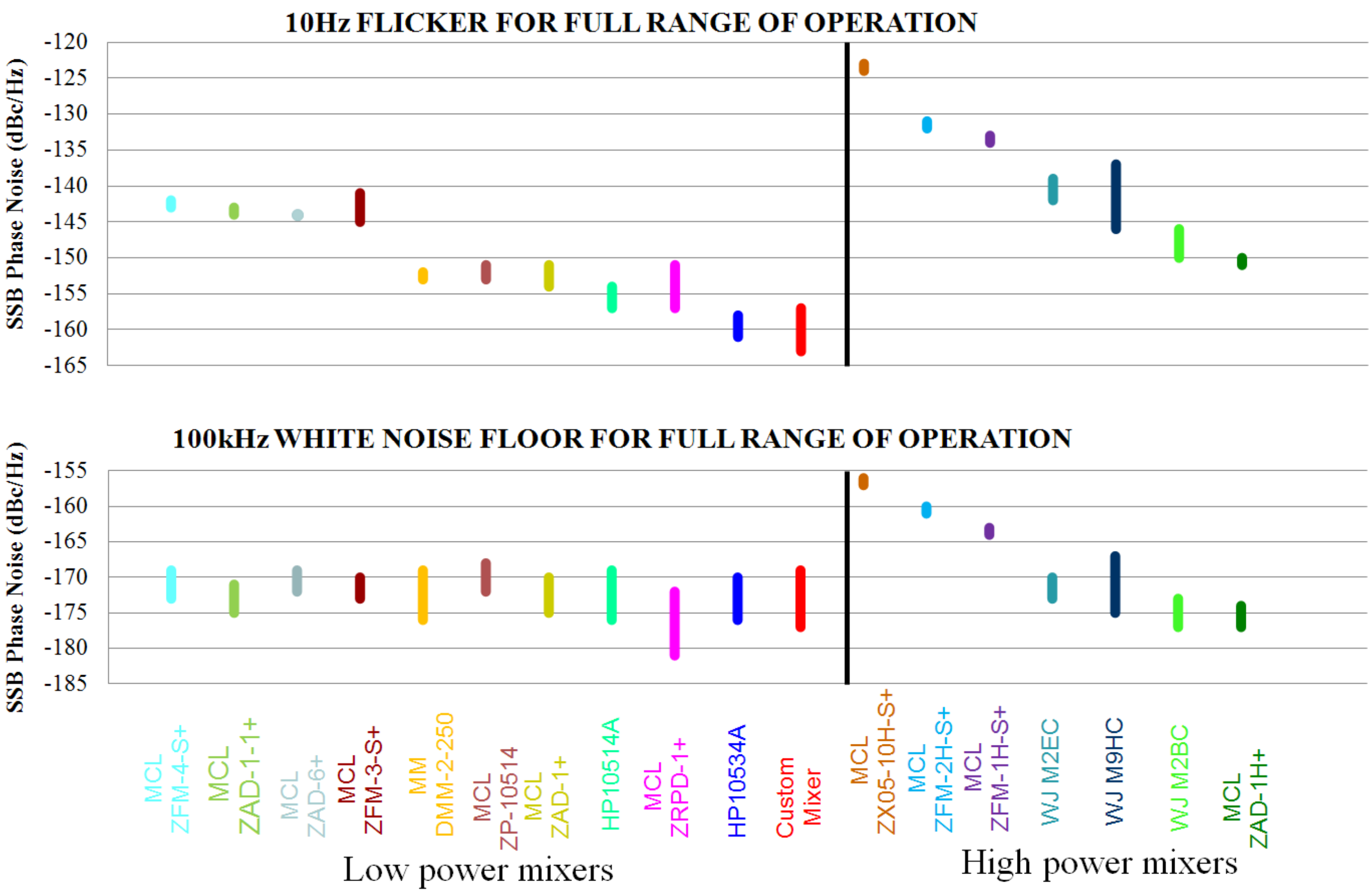

Figure 4. Residual PM noise summary of various phase detectors (endpoints indicate linear and saturated measurement limits).

IV. Custom Mixer Design

A. Mixer Design

The custom-built mixer listed in the summary of measurements was a simple double-balanced mixer with 2N2222A transistors in the diode ring. This design is discussed in a letter recently submitted for publication [13]. The custom detector is noteworthy because its flicker performance was the best in the detectors surveyed. Fig. 6 shows the general topology of the DBM. In this design there are four 2N2222A bipolar junction transistors (BJTs) used to construct a conventional double balanced diode ring.

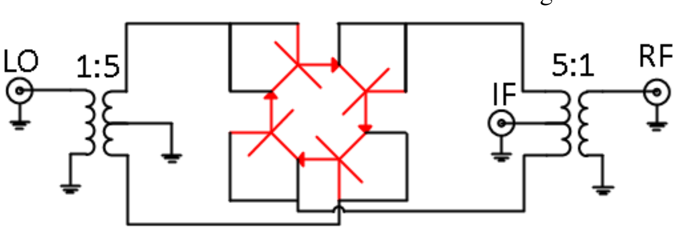

Figure 6. Double balanced mixer schematic. The diode ring in this double-balanced mixer is constructed by use of transistors with the collector input tied to the base.

We short the base to the collector of these BJTs and operate them as diodes by use of the emitter-base junction. The transformers used for this design are commercial off-the-shelf parts and have a 1:5 impedance ratio. This impedance ratio is chosen so that the input impedance of the reference frequency (RF) and local oscillator (LO) ports are nearly 50 Ω at 5 MHz. The mixer's input impedances are measured by use of the Smith chart display of a vector network analyzer.

B. Mixer Characterization

In order to measure the PM noise of the DBM, the nominal operating powers need to be found [3]. To determine the nominal LO power, a 4 MHz sinusoidal signal at -30 dBm is applied to the RF port of the mixer while the power of a 5 MHz signal at the LO port is varied. Conversion loss of the mixer is calculated by taking the power ratio of the 1 MHz beat at the intermediate frequency (IF) port to the RF signal at 5 MHz. A plot of conversion loss versus LO power is shown in Fig. 7. By use of this plot, the 1 dB compression point of the LO drive is found to occur at a level of +8 dBm. Operating the LO port in saturation is desired to reduce LO power fluctuation sensitivity. Taking the maximum allowed operating specifications of the transistors and transformers into account, a nominal LO drive of +11 dBm is selected. An additional measurement of conversion loss versus RF power at the selected nominal LO is made and plotted in Fig. 8. The 1 dB compression point of conversion loss at the RF port occurs at +5 dBm. All conversion loss tests for the mixer were conducted with a 50 Ω load at the IF port.

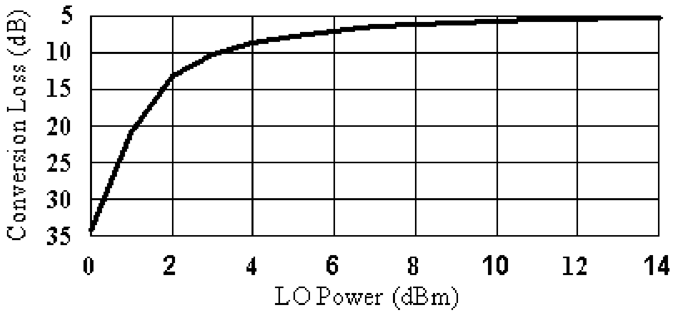

Figure 7. Conversion loss versus LO power of mixer with a -30 dBm RF power level. RF @ 4 MHz, LO @ 5 MHz, 50 Ω input impedance to FFT

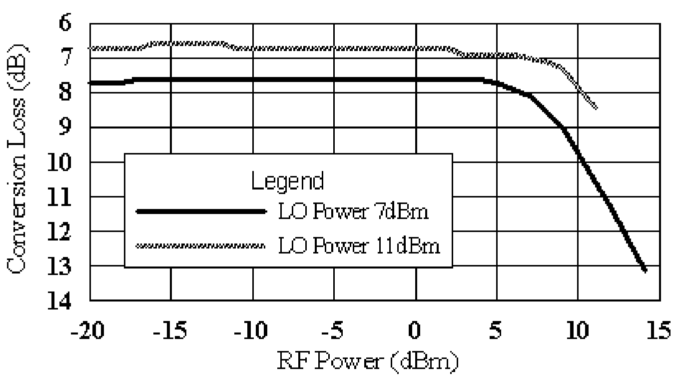

Figure 8. Conversion loss vs. RF signal power at constant LO drive powers. LO @ 4 MHz, RF @ 5 MHz, 50 Ω input impedance to FFT

Fig. 9 shows the results of the residual PM noise of this DBM design used as a phase detector. From these data it can be seen that the flicker noise of this device is L(10 Hz) = -161 dBc/Hz when the DBM is operated at LO = +11 dBm and RF = +5 dBm. In deep saturation (LO = RF = +11 dBm) the 10 Hz noise is improved to L(10 Hz) = -163 dBc/Hz. Both of these measurements show that this DBM has very low flicker noise as a phase detector.

V. Conclusion

We evaluated a number of phase detectors available in our lab at 5 MHz. A 40 dB range of flicker PM noise is observed among the surveyed detectors. Similar variation is also observed in the level of thermal PM noise. High-power mixers in general showed a higher level of flicker noise than that of the lower power detectors. We have found that for many phase detectors, the lowest noise floor is achieved while the device is operated in saturation. Since the sensitivity of the phase detectors depend on the impedance at the IF port, a further study of PM noise versus output termination design will be considered for future work. Specifically we will investigate the phase noise by use of non-absorptive terminations. Further investigation at other carrier frequencies will be conducted as well.

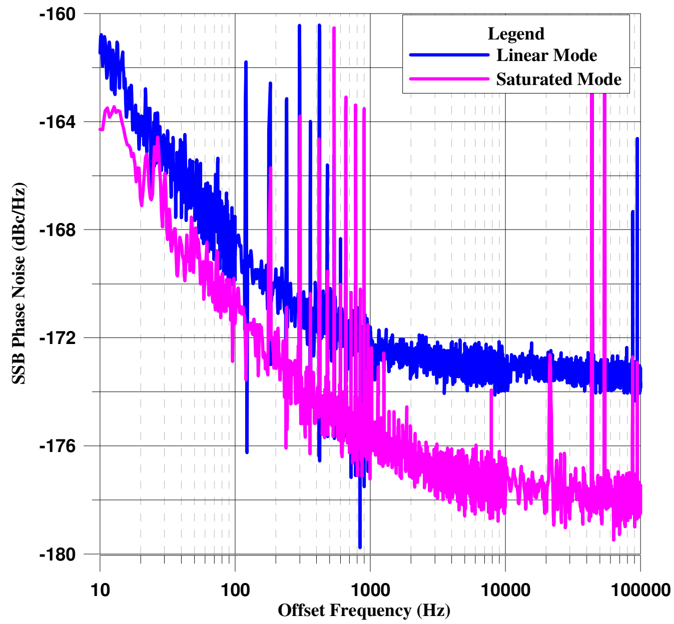

Figure 9. Cross-correlated residual PM noise floor of the 2N2222A based mixer in linear and saturated operation.

Acknowledgments

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