# W-band dual channel AM/PM noise measurement system — an update

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## Abstract

*We discuss the performance of a W-band (92-96) GHz amplitude modulated (AM) and phase modulated (PM) noise measurement system. The system uses two nearly identical channels to measure the residual noise in amplifiers in pulsed mode with a duty cycle of 10 % to 100 % (CW) at a given pulse repetition frequency (PRF). We describe details of the dual-channel measurement test set system and several design considerations that are essential for accurately extracting the device noise from measurement-system noise. We also discuss the modifications made to the synthesis scheme of the (92-96) GHz signal compared to the previous scheme. Finally, we present updated results for the source noise and the noise floor of the measurement system.*

## I. INTRODUCTION

There is an exponential growth in migration of many communications, radar, and programmable antenna systems to higher frequencies, in particular to W-band frequencies (75 – 110 GHz). The success of these high-speed digital systems depends critically on the ability to reduce the phase-noise of the reference oscillator and other electronics at W-band. It is the reference-oscillator's noise which sets the basic limit on many system performance criteria including jitter, bit-error-rate, sensitivity, resolution, and dynamic range of these high-speed digital systems [1]. At frequencies below 40 GHz, there are various suitable characterization techniques for oscillators, amplifiers and other components [2-4], while at W-band, characterization techniques are often inconsistent, subject to inaccuracies, or invalid due to high measurement noise. So, it is very important to develop measurement techniques at these higher frequencies to characterize these components. There are fewer discussions in the open literature [5-8] on strategies and issues associated with the state-of-the-art PM/AM noise measurements at W-band.

In this paper, we discuss the methodology, operation, and noise performance of the W-band PM/AM noise measurement system. The measurement system is designed principally to measure noise in amplifiers in pulsed mode with a duty cycle of 10 % to 100 % (CW) at a given pulse repetition frequency. We also report the results of PM noise for an InP amplifier. Section II describes the operation of W-band dual-channel cross-correlation PM/AM noise measurement system. In Section III, the PM noise performance of a phase-locked Gunn oscillator that has been used as a reference source at different frequencies is presented. This section also discusses difficulties in phase-locking an oscillator with a tuning range of over 4 GHz and how to overcome them. A comparison of PM noise of different components used in W-band synthesis is also presented in the same section. Experimental results of the PM noise floor of the W-band measurement system in pulsed mode with a duty cycle of 10 % to 100% (CW) at a given pulse repetition frequency are also included in this section. A summary is provided in Section IV.

## II. DUAL CHANNEL CROSS-CORRELATION PM/AM NOISE MEASUREMENT

A simplified block diagram of a dual-channel cross-correlation system [9-11] to measure PM/AM noise of an amplifier in pulsed mode is shown in Fig. 1. After amplification the (92-96) GHz signal is pulsed ON and OFF for a duty cycle of 10 % to 100 % at a given pulse repetition frequency (PRF) by use of a PIN diode switch. One part of the pulsed W-band signal is then fed to the device under test (DUT) and another part to the delay element (τ). These two



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signals are further split and fed to a two-channel system composed of two separate phase-noise measurement systems that operate simultaneously. Each comprises a power splitter, a phase shifter, and a mixer. The phase shifters establish true phase quadrature between two signals at the mixer inputs. The output (after amplification) of each mixer is fed to a two-channel cross-correlation fast Fourier transform (FFT) spectrum analyzer. The advantage of this technique is that only the coherent noise, i.e., noise of the DUT, that is present in both channels averages to a finite value. The time average of the incoherent noise processes approaches zero as √N, where N is the number of averages used in FFT. A diode detector is used to determine the precise duty cycle.

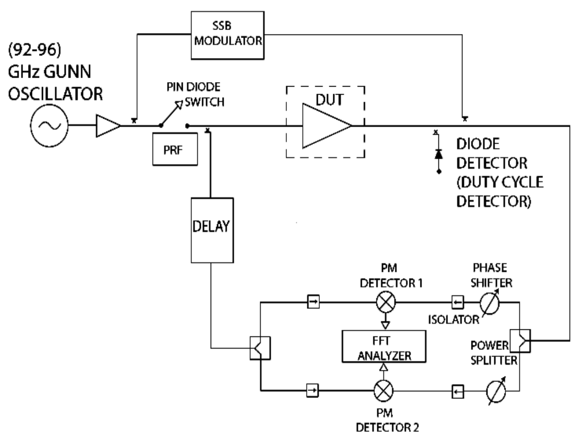


**Figure 1:** The residual PM noise of an amplifier (DUT) is measured with the configuration shown. Mixer and isolator noise in the top PM detectors are uncorrelated with respect to the bottom detectors. The PM noise of the (92-96) GHz oscillator signal is suppressed, since it appears equally at both inputs to the mixers.

As discussed, a pair of phase-sensitive detectors operates simultaneously. One input to the pair is the amplifier (DUT) plus source oscillator, and the other input to the pair is just the source oscillator. To avoid dispersion, a high degree of mechanical symmetry must exist between the phase bridges, one above and one below as shown at the bottom of Fig. 1. By laying out components so that the delays in each channel are identical, correlated noise plus signals are closely matched in phase at each bridge's mixer (PM detector). By matching the delay from each signal source, for example, when one source includes an amplifier or other DUT, then the PM noise of the (92-96) GHz driving reference source cancels to a high degree. Both of these factors are important in exploiting the benefits of the cross-correlation technique to ultimately measure the PM noise, introduced by the amplifier (DUT) as if it were driven by a perfect "noiseless" (92-96) GHz reference oscillator. Matching delays at W-band, however, is difficult, effecting a greater need to reduce noise in the W-band reference source. Table 1 gives PM noise criteria of the source and measurement system as requested by the sponsor for characterizing present-day lowest-noise amplifiers [5].

AM noise of an amplifier can be measured by use of the same set-up as in Fig. 1. The only requirement for an AM noise measurement is to tune each bridge to an in-phase condition between two signals at the mixer inputs.

**Table I.** PM noise criteria of W-band reference source and measurement system as requested by the sponsor. The power requirement at W-band is +13 dBm.

| Offset Frequency (kHz) | PM noise of W-band source L(f) dBc/Hz | PM noise floor 10 % / 100 % duty cycle L(f) dBc/Hz |
|---|---|---|
| 0.1 | -70 | -80 / -90 |
| 1 | -105 | -110 / -120 |
| 10 | -115 | -120/ -130 |
| 100 | -125 | -130/-140 |

A key requirement for high-accuracy noise measurements is to calibrate the dual measurement channels with precise PM and AM modulation. There are different approaches to calibrate the system: beat-frequency [12], AM/PM modulator [8, 13], noise standard [9]. We have used a single-sideband (SSB) modulation technique [7, 14] to calibrate our system.

## III. REFERENCE SOURCE AND ITS PM NOISE PERFORMANCE

A reference signal is required for the DUT. We have used a custom varactor-tuned Gunn oscillator as our reference source, which can be tuned to any frequency between 89 GHz to 96 GHz for a varactor voltage of 0 to 30 volts respectively. The PM noise of the free-running Gunn oscillator at 94 GHz using a delay-line discriminator technique [2] is shown in Fig. 2. The PM noise of the free-running Gunn oscillator is much higher than allowed by the criteria of Table I, but is not atypical. A $f^{-3}$ behavior persists over the five-decade range of $f$ shown. To meet the low-noise and power criteria in Table I requires considerable research, development, and attention to layout in the PLL, discussed next.

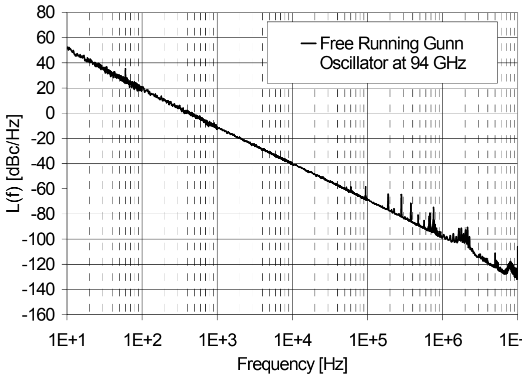


**Figure 2:** PM noise of free-running Gunn oscillator at 94 GHz with varactor bias voltage of +12 V.

The W-band signal that feeds the DUT is derived from a phase-locked Gunn oscillator. This reference source is tunable in discrete steps of 100 MHz over the widest possible range available in a single Gunn oscillator centered at 94 GHz, as much 4 GHz. Fig. 3 shows the scheme to lock the (92-96) GHz reference source. It consists of a varactor-tuned W-band Gunn oscillator, a NIST 10 GHz cavity-stabilized oscillator (CSO) [15], a ×9 multiplier, a 100 MHz crystal oscillator, a YIG tuned multiplier and a servo system. The 10 GHz signal from NIST CSO after ×9 multiplication is mixed with the (92-96) GHz signal from the Gunn oscillator to generate (2-6) GHz. Similarly, the 100 MHz signal from the crystal oscillator is fed to the YIG tuned multiplier to generate (2.1-6.1) GHz in discrete steps of 100 MHz. Then the (2.0-6.0) GHz and (2.1-6.1) GHz signals are mixed, which results in a 100 MHz output. This 100 MHz signal from the mixer and the 100 MHz signal from the crystal oscillator serve as two inputs of the phase detector (PD). The output of the PD after amplification in a servo amplifier and proper level shifting to ~30 V offset is fed to the varactor tuning port of the Gunn oscillator. The servo amplifier is a single-stage, second-order integrator with additional high-frequency compensation, giving a unity-gain bandwidth of about 5 MHz. The high-frequency compensation is needed in order to offset the roll-off of the voltage tuning response of the Gunn oscillator beyond about 1.5 MHz. Since the sensitivity of the Gunn oscillator that has been used as the reference source is approximately 200 MHz/volt, any voltage noise, e.g., power supply noise or the servo amplifier's noise, will affect the stability of the oscillator. We have used video amplifiers of very high slew rate, high-voltage swing, and low noise to permit reduction of noise of the reference synthesis to a nearly optimum theoretical noise limit. We measured the PM noise of the locked Gunn oscillator using single-channel two-oscillator method as shown in Fig. 4. The NIST W-band synthesizers #1 and #2 include components shown in Fig. 3. We tuned the two synthesizers to a desired frequency between (92-96) GHz and fed the outputs into a double balanced mixer. A PLL was used to lock the reference frequency to the test-oscillator frequency and to maintain quadrature between the two input signals to the mixer. The output voltage of the mixer is proportional to the difference between the phase fluctuations of the two sources. This voltage was amplified and its power spectral density was measured in a FFT analyzer. A noise standard has been inserted after the 10.0 GHz signal path of synthesizer #1 to calibrate the sensitivity of the measurement system.

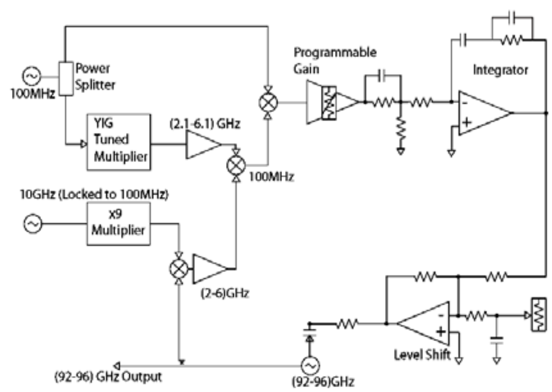


**Figure 3:** Schematic diagram of phase-locked (92-96) GHz Gunn oscillator/synthesizer.

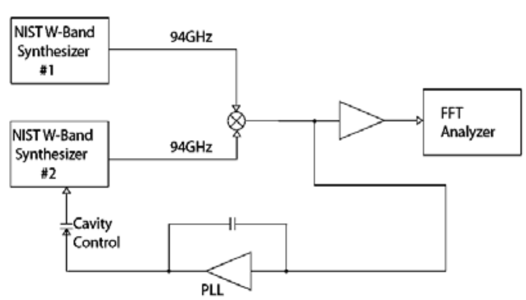


**Figure 4:** Single channel PM noise measurement set-up for 94.0 GHz source.

Fig. 5 shows the PM noise of the locked Gunn oscillator at different frequencies. It meets the specification as mentioned in Table I for almost all frequencies at all offset frequencies, however, there are some exceptions. For example, at 96.0 GHz the PM noise is higher at 1 kHz and 100 kHz offset frequencies. This is due to the fact that PM noise of the YIG-tuned multiplier at 6 GHz is dominating at 1 kHz offset frequency and the ×9 GaAs W-band multiplier noise is dominating at 100 kHz offset frequency. Fig. 6 shows the PM noise of YIG tuned multiplier and ×9 W-band multiplier.

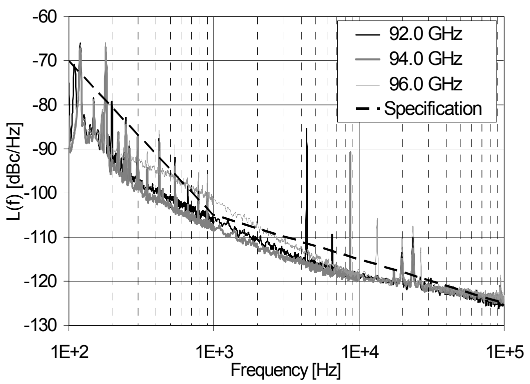


**Figure 5:** PM noise of locked Gunn oscillator at different frequencies. Measured phase noise is combined noise of a pair of similar oscillators. Noise of single oscillator is 0 to 3 dB better than shown.

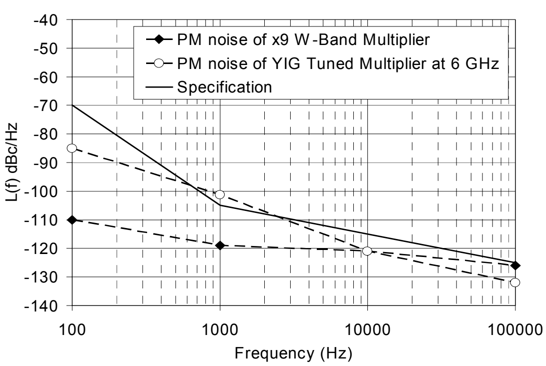


**Figure 6:** PM noise of ×9 W-band GaAs multiplier at 90 GHz and YIG tuned multiplier at 6 GHz. The noise of these components adds directly to the Gunn oscillator noise.

The PM noise floor of the W-band measurement system has been measured with a locked Gunn oscillator in CW mode of operation as well as in pulsed mode with a duty cycle of 10% at a given pulse repetition frequency, the result of which is shown in Fig. 7. These results are 20 dB to 30 dB better than our noise-floor criteria given in Table I.

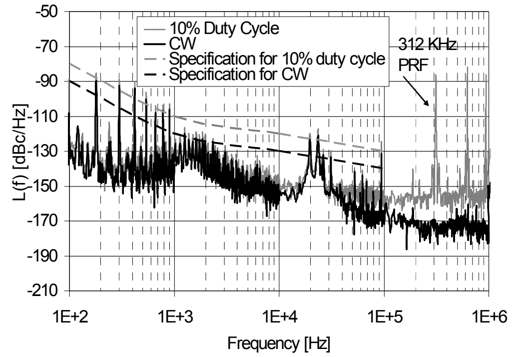


**Figure 7:** PM noise floor of the W-band measurement system at 94 GHz. PRF = 312 kHz and number of averages, N = 1000.

We have also measured the AM noise of combined Gunn oscillator and an amplifier (used to amplify source output power) using the same set-up as in Fig. 1 by tuning each bridge to an in-phase condition between two signals at the mixer inputs. The result is shown in Fig. 8 for 94 GHz.

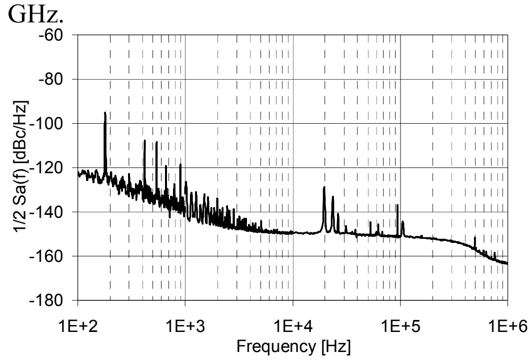


**Figure 8:** AM noise of locked Gunn oscillator at 94 GHz.

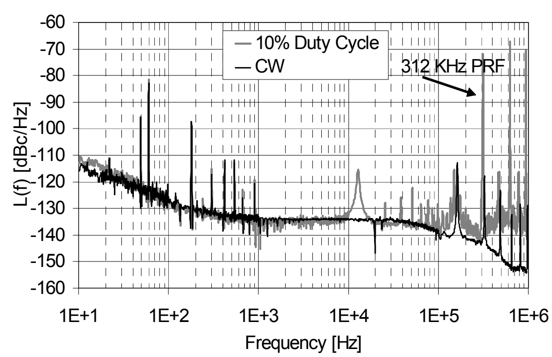


**Figure 9:** PM noise of InP Amplifier at 94 GHz, Pin = -2.5 dBm and PRF = 312 kHz.

Finally, we have measured the PM noise of an InP amplifier at 94 GHz in CW mode of operation as well as in pulsed mode with a duty cycle of 10 % at a given pulse repetition frequency, the result of which is shown in Fig. 9.

## IV. CONCLUSION

We have built a new dual-channel, cross-correlation noise-measurement system that works at W-band with a center frequency at 94 GHz. The most difficult challenge has been the generation, with sufficient power, of an ultra-low-noise synthesized reference signal covering 4 GHz. Using a single, custom-designed and built, and locked W-band oscillator. We met the challenge by properly selecting the W-band components and loop parameters. We measured the PM noise floor of the measurement system for CW mode of operation as well as for 10 % duty cycle and the results are 20 dB to 30 dB better than our noise-floor goal. We have found that for some frequencies W-band GaAs multipliers and YIG tuned multipliers have higher PM noise and have limited the noise performance of our synthesized reference phase-locked Gunn source. We have also measured the AM noise of Gunn oscillator and PM noise of an InP amplifier at 94 GHz. In the future, we plan to measure the effect of different amounts of phase delay on the PM noise floor as well as on the noise performance of other W-band device.

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