W-band dual channel PM/AM noise measurement system

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Abstract

We discuss the performance of a W-band (92-96GHz) PM and AM noise measurement system. The system uses two nearly identical channels to measure the AM or PM noise added by an amplifier or any passive component. It is designed principally to measure amplifiers in pulsed mode with a duty cycle of 5 % to 100 % (CW) at a given pulse repetition frequency. The system is calibrated by use of a single-sideband (SSB) modulator. We describe the details of the dual-channel measurement test set and several design considerations that are essential for accurately extracting device noise from measurement-system noise. Data are presented for the noise of the reference oscillator as well as for the measurement system's noise floor.

I. INTRODUCTION

The success of new high-speed, high-frequency electronic systems depends critically on the ability to reduce the phase noise of the reference (clock) signal and other electronics. At frequencies below 40 GHz, there are various suitable characterization techniques [1-3]. However, in the generation of a high-purity oscillator signal and the measurement of PM and AM noise in W-band, there are fewer discussions of state-of-the-art criteria and characterizations in the open literature [4-6].

We describe a W-band PM/AM noise measurement system capable of measuring noise of W-band amplifiers, mixers, oscillators, and other components and using low-noise techniques long established at X, Ku, and Ka bands. The measurement system is designed principally to measure amplifiers in pulsed mode with a duty cycle of 5 % to 100 % (CW) at a given pulse repetition frequency.

Section II describes the W-band dual-channel cross-correlation PM/AM noise measurement system. It also explains the calibration procedure using a single-sideband (SSB) modulator. Section III gives the PM noise performance of a free-running and phase-locked Gunn oscillator that has been used as a reference source. It also discusses difficulties in phase-locking an oscillator with over 4 GHz tuning range and how to overcome them. A comparison of PM noise of a x9 active W-band multiplier and locked Gunn oscillator is also given in this section. Experimental results of the PM noise floor of the W-band measurement system are also included in this section. Finally, the paper is summarized in Section IV.

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

To ensure that the noise contribution of the measurement system is much lower than the PM noise of an amplifier under test, a two-channel cross-correlation system for PM noise measurement is used [7-9]. A simplified block diagram to measure PM/AM noise of a pulsed amplifier is shown in figure 1. The 92-96 GHz signal is pulsed ON and OFF for a duty cycle of 5 % to 100 % at a given pulse repetition frequency (PRF) by use of PIN diode switch. One part of the pulsed signal is then fed to the device under test (DUT) and another part to the delay line. These two signals are further split and fed to a two-channel system comprised of two separate phase-noise measurement systems that operate simultaneously. Each is comprised of a power splitter, an amplifier, 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 approaches zero as $\sqrt{N}$, where N is the number of averages used in FFT. A diode detector is used to determine the precise duty cycle.

As discussed, a pair of phase-sensitive detectors operates simultaneously. One input to the pair is the amplifier plus source oscillator, and the other input to the pair is just the source oscillator. To avoid dispersion, a high degree of

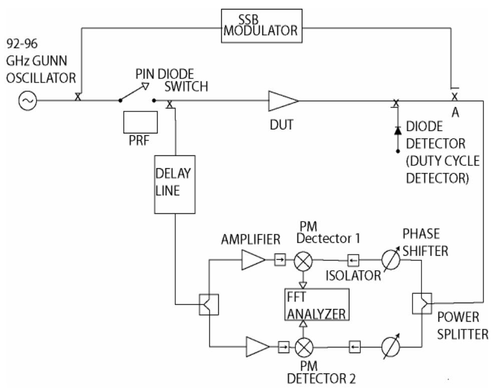

Figure 1: The residual PM noise of an amplifier (DUT) is measured with the configuration shown. Mixer, isolator, and measurement-system amplifier noise in the top PM detectors are uncorrelated with respect to the bottom detectors. The PM noise of the 92-96 GHz oscillator signal is suppressed, since it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

mechanical symmetry must exist between the phase bridges, one above and one below as shown. 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 noise, $\mathcal{L}(f)$, 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, affecting a greater need to reduce noise in the W-band reference source. Table 1 gives PM noise criteria of the source and measurement system for characterizing present-day lowest-noise amplifiers [4].

Figure 2 shows a cross-correlation AM noise measurement system for an amplifier that reduces the noise floor of the measurement system. A reference source drives the test amplifier, the amplifier output is split, and each channel is fed into an AM detector. The output signals of the detector are then amplified and measured with a two-channel FFT spectrum analyzer. Each detector has intrinsic noise that is uncorrelated relative to the other detector, and hence this noise will be reduced by a factor of $\sqrt{N}$, as discussed before. However, the source noise is correlated. A limiter is placed after the source to reduce its AM noise. Instead of using AM detectors, AM noise of an amplifier can be measured using the same set-up as in Figure 1.

Table 1. PM noise criteria of W-band reference source and measurement system.

PM noise of W-band source dBc/Hz	PM noise floor 10 % / 100 % duty cycle dBc/Hz
$\mathcal{L}$(100 Hz) = -70	$\mathcal{L}$ (100 Hz) = -80 / -90
$\mathcal{L}$ (1 kHz) = -105	$\mathcal{L}$ (1 kHz)= -110 / -110
$\mathcal{L}$ (10 kHz) = -115	$\mathcal{L}$ (10 kHz) = -120 / -130
$\mathcal{L}$ (100 kHz)= -125	$\mathcal{L}$ (100 kHz)= -130 / -140

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.

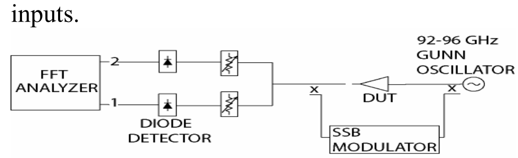

Figure 2: Parallel AM detectors are connected to each channel of a cross-correlation analyzer. The configuration shown in Figure 1 is altered to conform to this arrangement for measurement of AM amplifier noise.

A key requirement for high-accuracy noise measurements is to calibrate the dual measurement channels using precise PM and AM modulation. There are different approaches to calibration of the system: beat-frequency [10], AM/PM modulator [6, 11], noise standard [7], and single-sideband (SSB) modulation [12] are most common.

Figure 3 shows the diagram of a special SSB modulator used to calibrate the sensitivity of the PM and AM measurement test set. The SSB modulator is composed of a 90^o quadrature hybrid, two single sideband mixers, a 90^o phase shifter and a power summer. This modulator produces a SSB tone that is a constant amount β^2 below the input signal and can be tuned to Fourier frequency offsets from dc to over 20 MHz by changing the IF frequency. β^2 is determined by measuring the SSB power relative to the carrier signal at point A in Figure 1. When combined with the carrier at point A, the SSB signal produces upper and lower PM and AM sidebands that are precisely equal in amplitude, offset from the carrier by the IF frequency and $\beta^2/4$ below the carrier. These reference signals are then used to calibrate the sensitivity of the system when adjusted to measure either PM or AM noise [12]

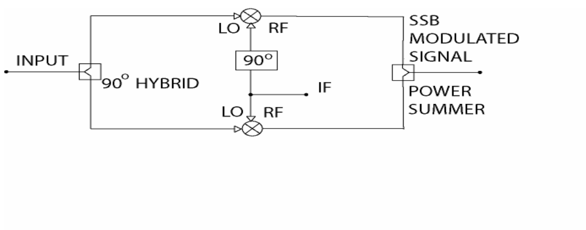

Figure 3: The SSB modulation scheme for calibrating PM/AM noise measurement system.

III. REFERENCE SOURCE AND ITS PM NOISE PERFORMANCE

A reference signal is required for the DUT. The dual-channel system described here consists of a two-channel phase or amplitude bridge that is configured to measure the additive noise of the DUT and simultaneously suppress the noise introduced by the reference signal. While it is true that the PM noise of the reference cancels to a high degree, suppression of its noise is limited by an ability to precisely match the delays in each half of each bridge. A conservative estimate of suppression, one based on pulsed operation and unknown non linearities and delays in the DUT, is –30 dB at offset frequency, f = 200 kHz. Therefore, in order to meet the pulsed and CW measurement-system noise floor listed in Table 1, the oscillator can conservatively have 30 dB worst noise. However, this tolerable level of reference-oscillator performance does not permit the reference and measurement system to be used for another purpose, namely to measure the noise of a typical low-noise oscillator as the DUT. Rather than restrict the prospective use of the measurement system, it is sensible to design the reference source with the lowest possible noise.

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. We have measured the PM noise of a free-running Gunn oscillator at 94 GHz using delay-line discriminator technique [2], and the result is shown in comparisons of Figure 6. The PM noise of the free-running Gunn oscillator is much higher than the criteria of Table 1, but is not atypical. A f^{-3} behavior persists over the five-decade range of f shown. To meet the low-noise criteria in Table 1 requires considerable research, development, and attention to layout in the PLL, discussed next.

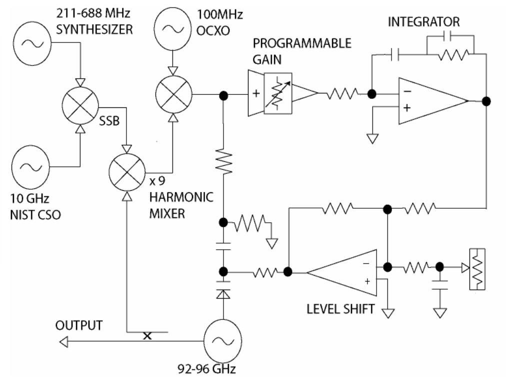

Figure 4: Schematic diagram of phase-locked 92-96 GHz Gunn oscillator.

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. Figure 4 shows the scheme to lock the 92-96 GHz reference source. It consists of a NIST 10 GHz cavity-stabilized oscillator (CSO) [13], an rf frequency synthesizer capable of generating 211 MHz to 688 MHz in steps of 11 MHz, a x9 harmonic mixer, a varactor-tuned Gunn oscillator and a servo system. The 10 GHz signal from NIST CSO is first mixed with the desired frequency from the 211-688 MHz synthesizer in a single sideband mixer. The output of the mixer is then fed to the local oscillator (LO) port of the x9 harmonic mixer, while the output of the Gunn oscillator is fed to the RF port. The frequency of the Gunn is adjusted so that the IF from the x9 harmonic mixer is 100 MHz. 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 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 2

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 very high slew-rate, low-noise servo amplifiers (video) to permit noise reduction of the reference synthesis to a nearly optimum theoretical noise limit. We measured the locked Gunn oscillator PM noise using the method shown in Figure 5. For low measurement phase noise, we used a fixed-frequency 10 GHz Sapphire loaded cavity oscillator (SLCO) and 500 MHz reference also configured and shown in Figure 5. These two signal are mixed together to generate 10.5 GHz, which is further multiplied by 9 by use of an active GaAs multiplier to generate 94.5 GHz.

We have separately measured our GaAs multipliers and found that they have PM noise that is below the noise of our synthesized reference phase-locked Gunn source, (see figure 6). Multipliers are suitable for fixed-frequency ultra-low noise signals. Their spurious multiplication by-products must be considered if they are to be used as the source signal for a noise-measurement system.

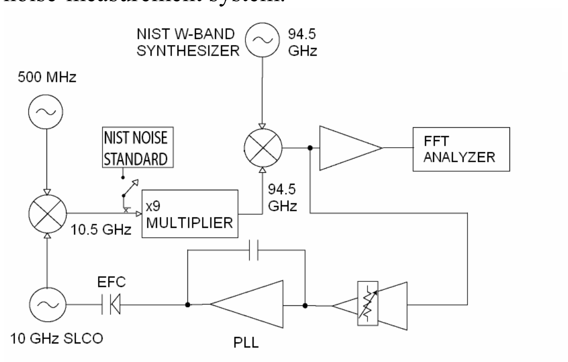

Figure 5: Single channel PM noise measurement set-up for 94.5 GHz source.

The output of the multiplier and synthesizer, tuned to 94.5 GHz, the synthesizer being the DUT, are fed into a double balanced mixer. A PLL is 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 is amplified and its power spectral density is measured in a FFT analyzer. A noise standard has been inserted after 10.5 GHz signal path to calibrate the sensitivity of the measurement system. Figure 6 shows the PM noise of the locked Gunn oscillator, which is much lower than that of the free-running Gunn oscillator; however, it is still higher than the expected value. This is due to the fact that noise of 500 MHz synthesizer in the measurement is dominating.

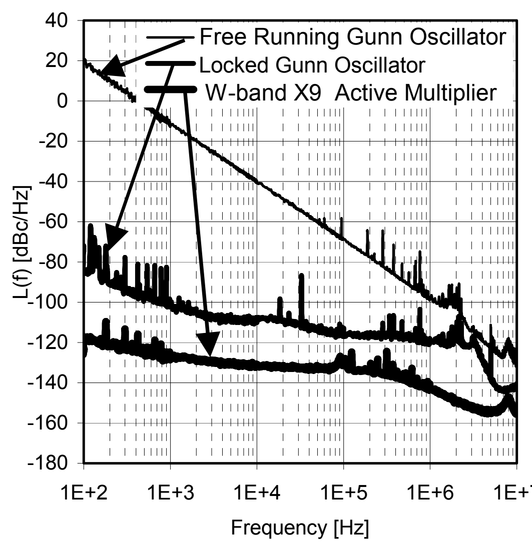

Figure 6: PM noise of the free-running Gunn oscillator, locked Gunn oscillator, and x9 GaAs W-band multiplier.

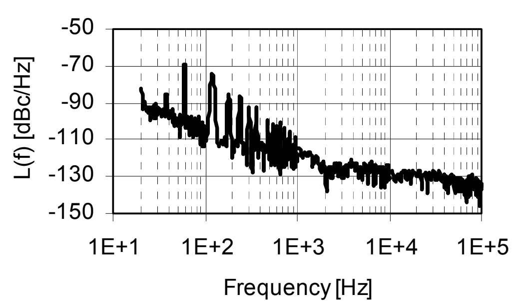

Figure 7: PM noise floor of the W-band measurement system.

We are presently involved in developing a low-noise measurement system to measure the PM noise of our 92-96 GHz source. The PM noise floor of W-band measurement system has been measured with a locked Gunn oscillator, the result of which is shown in Figure 7. This result meets the CW criteria given in Table 1.

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. We have also measured the PM noise floor of the measurement system for CW mode of operation, and it complies with our noise-floor criteria. The most difficult challenge has been the generation of an ultra-low-noise synthesized reference signal covering 4 GHz from a single locked W-band oscillator. The voltage tuning sensitivity of the varactor tuned Gunn oscillator had to be very high to cover this range, in addition to its having a usual high level of intrinsic f^{-3} PM noise. Low-noise, very high slew rate, large signal video amplifiers and careful layout were used in a type-two servo integrator to reduce noise of the reference synthesizer to a near-optimum theoretical noise limit. For measurements of the PM noise of the reference, we have found that GaAs multipliers have PM noise that is below the noise of our synthesized reference phase-locked Gunn source.

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