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A 100 GHz AM and PM NOISE MEASUREMENT SYSTEM: PRELIMINARY DESIGN and PERFORMANCE[1]

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Abstract

A 100 GHz AM and PM noise measurement system is described. The basic approach to its construction is to apply existing state-of-the-art, cross-correlation noise measurement techniques to 100 GHz (W-band). The system uses two amplitude-noise and phase-noise detectors operating in parallel with cross-correlation spectrum analysis so that measurement-system noise averages down as $m^{-(1/2)}$*, given m available averages. The approach, widely regarded at lower frequencies as the dual-channel PM/AM noise measurement approach, has some new considerations in extending the frequency range to W-band. A new AM/PM modulator used to calibrate the 100 GHz measurement system is discussed. Data are presented for the measurement system's noise floor. We give AM and PM noise measurements of an InP amplifier with a gain of 10 dB to 15 dB.*

I. INTRODUCTION

With the increase in operating rf frequencies of many communications, radar, and programmable antenna systems, it is important to develop spectral purity measurement techniques at these higher frequencies. In particular, the advent of 100 GHz logic gates has created a significant revival in interest and applications in this range of frequencies (W-band) from existing lower-frequency applications. In support of this activity, NIST has developed a new AM and PM noise measurement system for oscillators and amplifiers operating at 100 GHz. Presently, the primary use is in evaluating 100 GHz clock signals used in high-speed digital signal processors (DSP), arbitrary waveform generators, analog-to-digital converters (ADC), and broadband telecommunications signal protocols. At frequencies below 40 GHz, there are suitable measurement and characterization techniques [1-3], while at W-band, characterization techniques are often not consistent [4,5]. In particular at 100 GHz, reference (or clock) noise sets a basic limit on many system performance criteria including for example jitter, bit-error-rate, sensitivity, and dynamic range of high-speed digital and signal-processing systems [6].

This paper is necessarily descriptive as opposed to theoretical. It points out strategies and issues associated with making state-of-the-art noise measurements at W-band. Section II defines the rationalle for using the so-called dual-channel cross-correlation measurement technique. Section III describes the apparatus, including a calibrated AM/PM modulator. Sections IV and V explain how AM and PM cross-correlation measurements are done using the apparatus. Section VI presents measurements of a 100 GHz InP amplifier. Section VII and VIII give a technique for measuring the PM noise of an oscillator by using a clean reference oscillator derived from a 10 GHz laboratory reference. The technique for obtaining the phase-locked 100 GHz reference is described.

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II. MOTIVATION FOR DUAL-CHANNEL CROSS-CORRELATION MEASUREMENTS

This writing assumes familiarity with the subject of how to measure the AM and PM noise on an otherwise ideal oscillating signal. AM level is typically measured using a circuit that rectifies a carrier oscillating signal and produces the absolute value of the signal, essentially converting a.c. to d.c. This rectified output is filtered to separate AM noise modulation from the normal carrier and other high-order signals [1,2].

PM noise is determined by measuring phase fluctuations relative to nominal phase by using a phase discriminator. Alternatively, phase fluctuations between a reference oscillator and test oscillator can be measured by mixing the two oscillator signals 90° out of phase (phase quadrature) in a phase-locked-loop configuration. The two oscillators are at the same frequency in long-term as guaranteed by the phase-lock loop (PLL). A low-pass filter (to filter the RF sum component) is used after the mixer since the difference (baseband signal) frequency is the one of interest. By holding the two signals at relative phase quadrature, short-term (that is, uncorrected) phase fluctuations between the test and reference oscillators will appear as voltage fluctuations out of the mixer, and these voltage fluctuations can be analyzed by a conventional spectrum analyzer [7-10].

An inherent assumption in the above description of the phase noise measurement process is that the reference oscillator and the components used in the phase-locked loop and the mixer are ideal noiseless devices. While this is normally a valid assumption for measurements of moderate accuracy at lower frequencies up to about X-band, it breaks down in the case of precise measurements of phase noise of very low noise oscillators or other devices. In such cases, it is common to use the dual-channel or the so-called cross-correlation technique [11].

In case of measurements of a very low noise oscillator, one uses two independent reference oscillators (which are probably as noisy as the oscillator under test). With each one of these references, one then configures a single-channel setup as described in the previous paragraph. The voltage fluctuations out of the mixers of the two channels are then fed to the two inputs of a dual-channel dynamic signal analyzer. Each channel computes $S_{1,2}(f)$=FT $V_{DUT\ OSC}(t)$ x FT $V_{REF\ OSC}(t)$, where FT is a Fourier Transform operator. Thus, in the cross-correlation output between the two channels, only the FT $V_{DUT\ OSC}(t)$ is observed because the uncorrelated terms due to the two references approaches zero as $1/[\sqrt{(2m)}]$, where m is an average of the number of complete blocks of data that undergo Fourier transforms, down to the limit of the uncertainty on the uncorrelated noise.

While dealing with phase noise measurements at W-band, the noise in the components of the system becomes an even greater issue. The 1/f noise in the mixers and to some extent in isolators and circulators become comparable to or even greater than the noise in the amplifiers and oscillators to be tested. There is also a problem of high conversion loss in the harmonic mixers that are used for up-conversion to the W-band. Even getting up to and maintaining signal levels of +20 dBm can be a problem in the measurement system because of the high waveguide attenuation. Thus, even for making measurements with a modest accuracy goal, use of a cross-correlation system becomes imperative.

III. DESCRIPTION OF MEASUREMENT TEST SET

An important factor in the design of a dual-channel PM/AM noise measurement system for W-band is compactness. While X-band systems can be built with a great deal of flexibility to accommodate a variety of component and dimensional changes by using coaxial components, W-band systems do not have the same flexibility. This is because of the necessity of using waveguide components. Long or contorted signal paths are a detriment to phase matching and also cause significant signal attenuation. Additionally, some specialized components that are needed at W-band are awkward and bulky, hence cumbersome to use. Consequently, the hardware of the system's two channels of phase and amplitude detection must be integrated in a carefully planned way.

Figure 1 on its left shows a photograph of the AM/PM noise measurement apparatus, while the right side shows a simplified diagram of the basic waveguide hookup. Note the high degree of mechanical symmetry between the phase bridges, one on the left (channel 1) and right (channel 2). By laying out components so that the delays in channel 1 and channel 2 are identical, correlated noise plus signals are closely matched in phase at each bridge's mixer. By adjusting the delay from each signal source, for example, when one source includes an amplifier or other DUT, then the PM noise of the 100 GHz driving reference source cancels to a high degree. Both of these factors are important in exploiting the benefits of the cross-correlation technique.

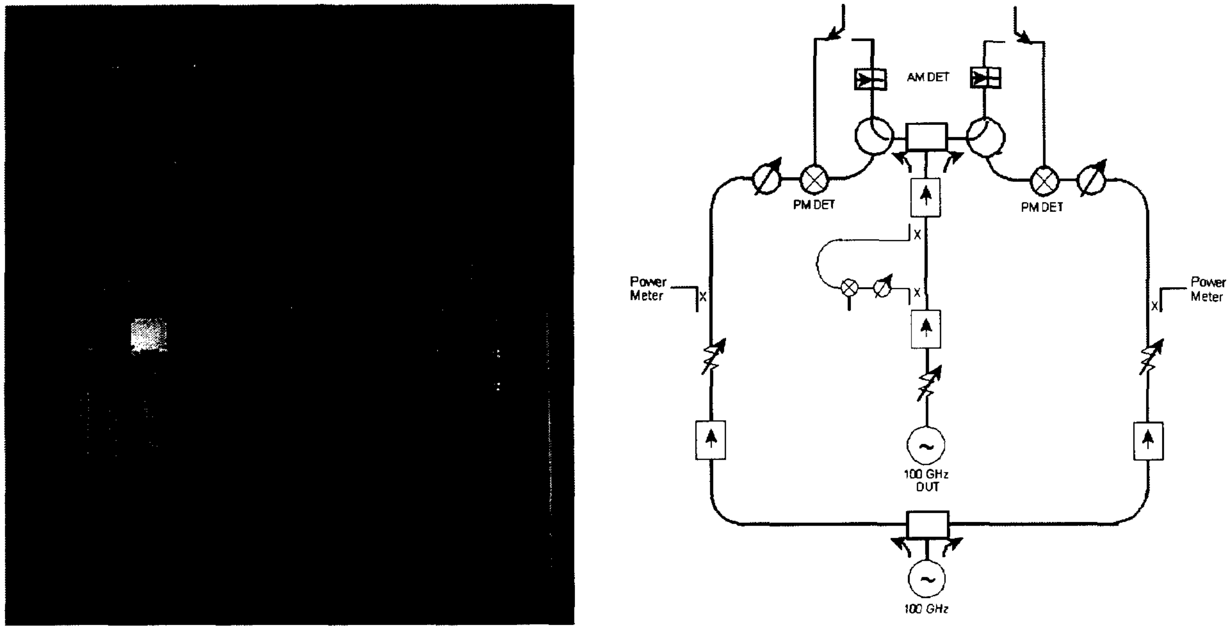

Figure 1: Photograph (left) of W-band noise measurement apparatus and its schematic (right).

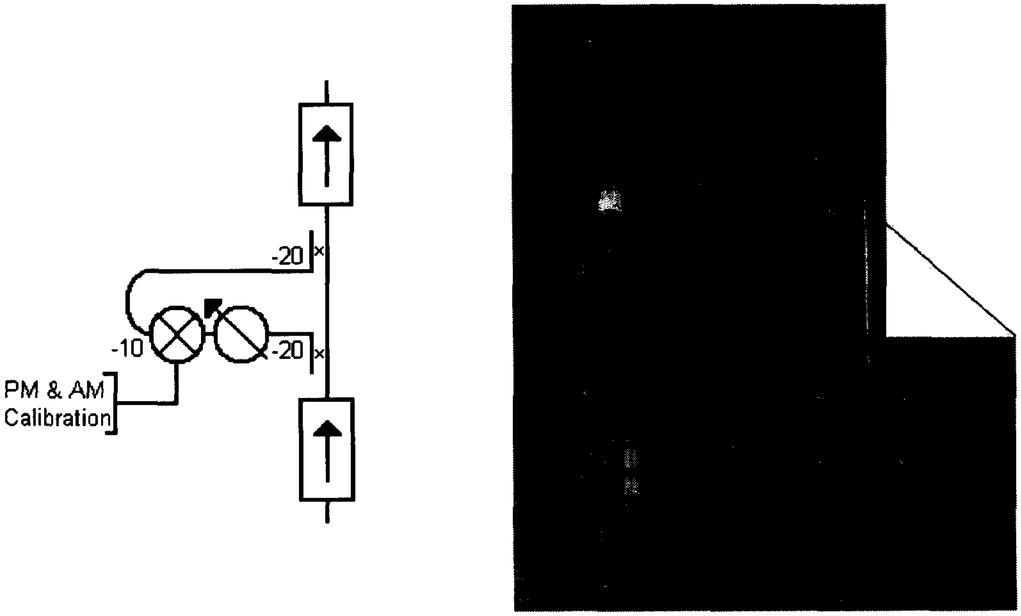

Figure 2: The modulator is capable of introducing a fixed level of pure AM or PM modulation.

A key ability in noise measurements such as these is to perform *in situ* calibration of the dual measurement channels using precise PM and AM modulation. This substantially improves accuracy of PM and AM noise measurements. Figure 2 shows a diagram and picture of the modulator used to calibrate the sensitivity of the AM and PM measurement test set. While this modulator has been described and successfully deployed for operation at lower frequencies [12], a main objective here was to translate the technique to a modulator at 100 GHz. The important property of this modulator is that it can introduce pure AM or PM modulation into the measurement system at a variety of offset Fourier frequencies and at a known level. Cross guide directional couplers are used for compactness, along with isolators at both the input and output.

IV. CROSS-CORRELATION AM NOISE MEASUREMENT

By feeding the signal under test into two AM detectors that are operating in parallel, one obtains two voltages $V_1(t)$ and $V_2(t)$ whose rms values are proportional to AM level for a data run t in seconds s. Each detector has intrinsic noise that is uncorrelated relative to the other detector. We extract a measurement of the cross-power spectral-density feature of a two-channel dynamic signal analyzer in order that uncorrelated noise is averaged down as discussed earlier.

Figure 3 shows a diagram of the setup for the parallel AM detectors. One notes that the AM noise floor is determined by the residual AM noise of the 100 GHz source oscillator. There is no way to suppress the AM noise of the 100 GHz reference oscillator in this measurement system.

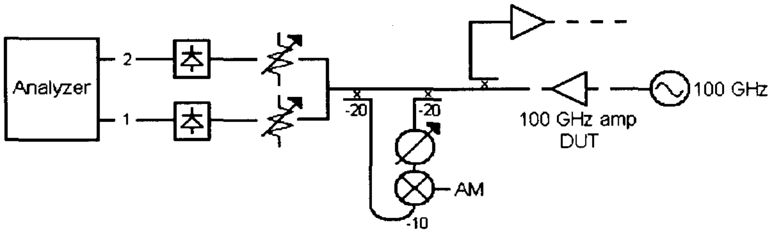

Figure 3: Parallel AM detectors are connected to each channel of a cross-correlation analyzer.

V. CROSS-CORRELATION PM NOISE MEASUREMENT

Measurement of PM noise of devices at 100 GHz is by two nearly identical phase bridges whose phase deviations are analyzed simultaneously using a cross-spectrum analyzer. The phase bridges are shown in figure 4. Similar to the dual-channel AM scheme, the correlated spectrum, here being the PM noise of a device under test such as an amplifier is extracted; uncorrelated noise from components in each bridge averages down, thus lowering the measurement system's noise floor and enhancing the precision of the estimate of PM noise.

Measurement of device PM noise differs from that of device AM noise in that the PM noise of the source oscillator cancels to a high degree. Note that the measurement is configured in such a way that the noise of the oscillator is present on both inputs of the mixers, leaving the noise of the amplifier that we wish to measure. As discussed, a pair of phase-sensitive detectors operate simultaneously, one measuring the amplifier plus source oscillator, and the other measuring just the source oscillator. Thus, $\mathcal{L}(f)$ is the noise of the amplifier whose input would be regarded as from a perfect ``noiseless" 100 GHz reference clock.

We plan to install two +12 dB 100 GHz amplifiers (pointed to by vertical arrows on right of figure 4) to increase input sensitivity of the cross-correlation measurement system. Their additive noise is uncorrelated and so will effectively decrease the measurement system noise floor with the increase of sensitivity by about +12 dB. These amplifiers are essential for state-of-the-art amplifier noise measurements, especially for anticipated DUT's operating at low temperatures potentially down to 4 K.

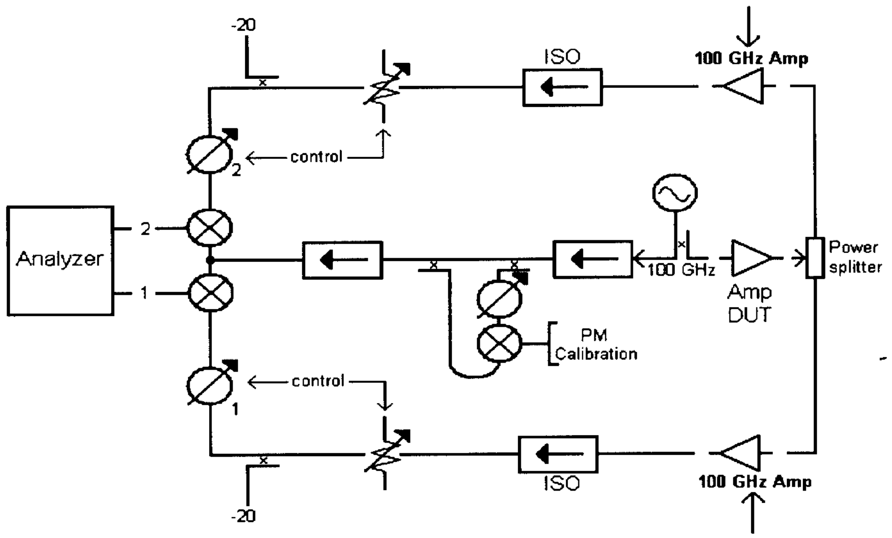

Figure 4: The residual PM noise of an amplifier (DUT) is measured with the configuration shown. Both mixer noise and 100 GHz oscillator noise is suppressed.

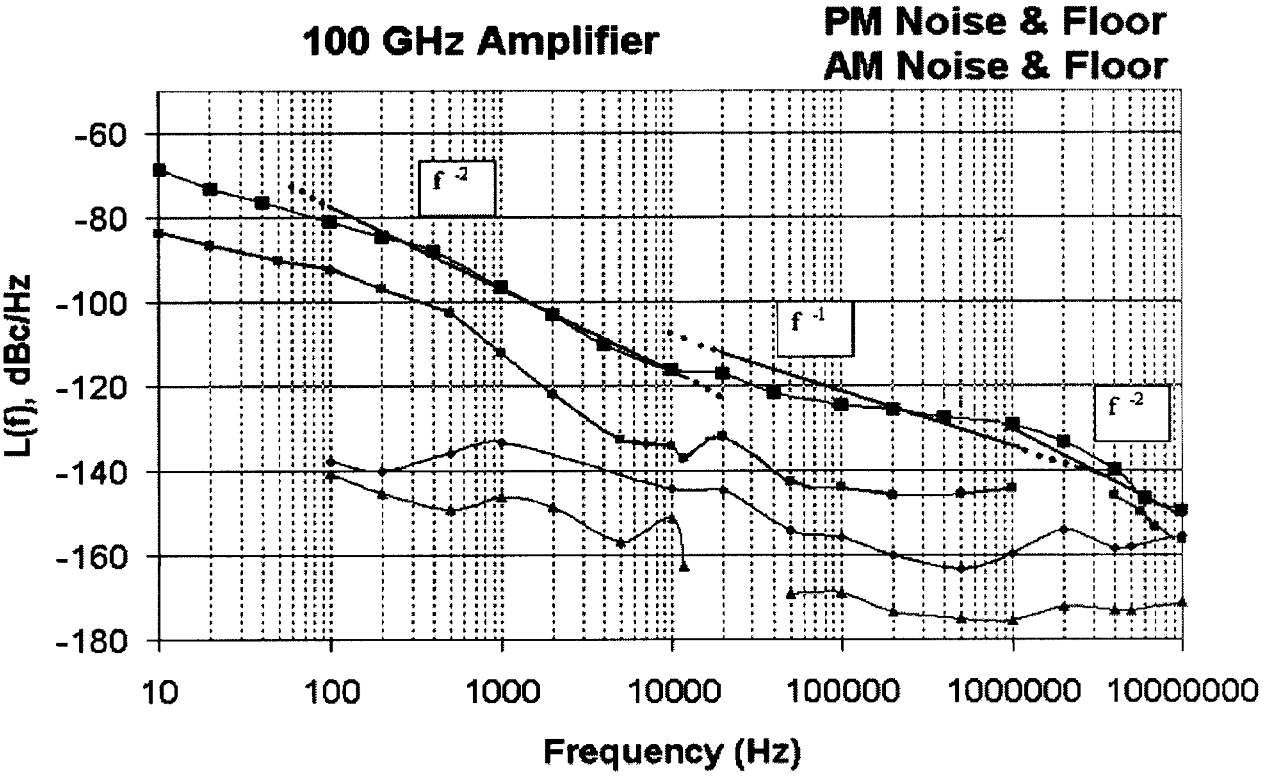

Figure 5: The top plots are, respectively, the measured PM noise of a InP amplifier with gain at +10 dB and the corresponding system PM noise floor when operating at 100 GHz. AM noise and floor are respectively indicated by the two bottom plots. The gaps are regions where spectral lines of unknown origin were observed.

VI. PM & AM NOISE MEASUREMENTS OF 100 GHZ AMPLIFIER

$\mathcal{L}(f)$ of a 100 GHz InP amplifier for use with a reference clock signal is shown as the upper curve in figure 5. The amplifier has a gain of 10 dB to 15 dB (depending on gate bias currents) with an output level of +13 dBm. The lower three plots in descending order are (1) PM noise floor with the amplifier removed and replaced by a waveguide connection, (2) AM noise of the amplifier, and (3) amplifier-removed AM measurement noise floor.

There are three segments indicated on the plot of amplifier PM noise, corresponding to f^{-2} from 10 to 10 000 Hz, f^{-1} from 10 kHz to 1 MHz, and again f^{-2} from 1 to 10 MHz. Interestingly, there are no regions of f^{0}, or white PM noise, while white AM noise is observed from 0.1 MHz to 10 MHz.

Results show that the use of the amplifier with an ideal reference source would set a lower limit on clock jitter of between 1 and 10 fs for delays from 200 ns to 20 ms . This performance is commendable and is better than the minimum jitter level needed for the signal-processing application involving this amplifier [6].

VII. PM NOISE MEASUREMENT OF AN OSCILLATOR

Figure 6 shows a simplified block diagram of the two phase bridges, one used to phase-lock a 100 GHz reference oscillator. The 100 GHz reference is phase-locked to a 10 GHz SLCO, which is in turn phase-locked to a test oscillator, the device under test, or DUT. In this case, the PM noise of the reference must be below that of the DUT oscillator. The next section describes the details of obtaining a clean reference. The use of dual phase bridges and a cross-correlation analyzer allow uncorrelated phase-detector noise to average down, as described earlier.

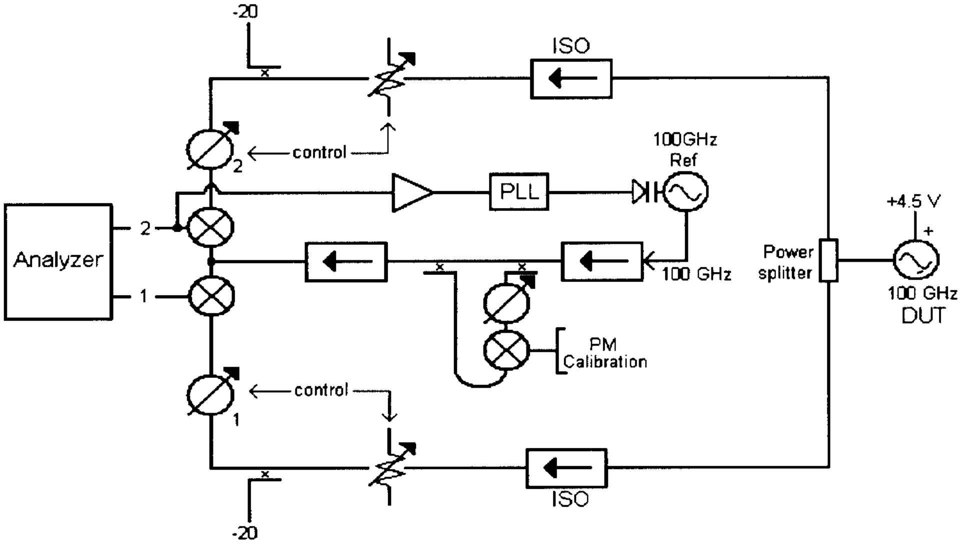

Figure 6: A phase-locked loop is used for measuring the relative PM noise between a reference and DUT 100 GHz oscillator. Noise from the mixers and measurement system components is suppressed by the cross-correlation method. PM noise of the reference oscillator must be lower than the DUT oscillator by at least 10 dB over the range of Fourier frequencies of interest.

VIII. TECHNICAL APPROACH TO REFERENCE SOURCE

The measurement system's reference signal is from a cavity-stabilized 50 GHz Gunn oscillator and doubled to 100 GHz as described here. Basically, two microwave regenerative frequency dividers and a mixer provide a coherent 10 GHz output that is phase-locked to a low phase noise sapphire-loaded cavity oscillator (SLCO) as shown in figure 7.

A cavity-stabilized GaAs Gunn-diode oscillator serves as a low-noise reference signal, a key development effort at NIST. The diode is contained in a housing that has low-Q resonances at both 50 and 100 GHz; thus two harmonically-related signals are present. An iris couples power at 50 GHz to a stabilizing cylindrical cavity made of material with a low coefficient of linear expansion (Invar). This significantly reduces frequency change with temperature change. The design of the iris is central to the operation of the oscillator. It couples 50 GHz from the diode to the correct high-order cavity mode without spoiling the high loaded cavity Q, while it reflects 100 GHz. A WR-10 waveguide out of the diode housing extracts about 25 mW of power at 100 GHz through a junction isolator. This strong signal is used as the source for the noise measurement system. About 1 mW of 50 GHz signal is extracted from the stabilizing cavity through a small coupling slot that launches into standard WR-19 waveguide, then through a junction isolator. This signal is used to phase-lock the Gunn oscillator to a 10 GHz laboratory reference by mixing and by the use of microwave regenerative frequency dividers [13-16]. The scheme is shown in figure 7.

Since the 10 GHz reference is an ultra low phase noise SLCO, the broadband phase noise of the 100 GHz Gunn-oscillator is limited by mixer/divider noise if the bandwidth of the PLL is sufficiently high (>1 MHz). The 50 (or 100) GHz frequency is controlled by the DC voltage that powers the Gunn-diode, thus the phase error voltage is used to control power supply voltage. This driver has a frequency control bandwidth of only about 100 kHz. For offset frequencies greater than about 100 kHz, the phase noise of the 100 GHz source must then be comparable to or better than that of the sapphire-loaded cavity oscillator (SLCO) when normalized to 100 GHz, which is not the case. Thus a high-pass filter is used to flatten and extend the PLL's response. An ideal conjugate filter would extend the bandwidth to an arbitrarily high value, but the bandwidth has a practical limit of about 250 kHz before the PLL becomes unstable and oscillates. So a remaining goal is to improvise a scheme for control of the wideband phase or frequency of the Gunn-oscillator. Under the best conditions, the phase noise of the 100 GHz source principally would be set by mixer/divider noise, and close to carrier, the noise would be set by the SLCO stabilized by a reference with good long-term frequency stability [17-20].

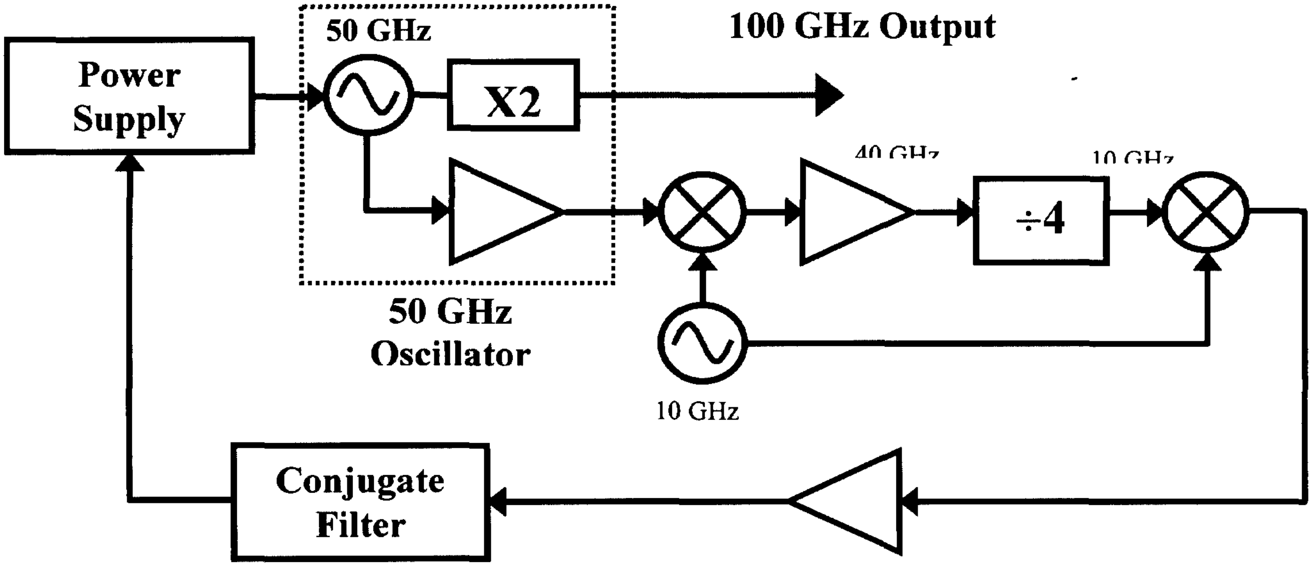

Figure 7: A low PM noise 100 GHz reference signal is obtained by phase locking a stabilized 50 GHz Gunn-diode oscillator with a 100 GHz output to a 10 GHz reference using the scheme shown. The 10 GHz reference is a low PM noise SLCO.

IX. SUMMARY

We have constructed a dual channel (cross-correlation) measurement system and have measured the AM and PM noise of a 100 GHz InP amplifier with gain of 10 dB to 15 dB, depending on gate bias currents, which was operating at room temperature. The measurement system AM noise floor is commendable, achieving the thermal limit for f > 10 kHz. While the PM noise floor is not as good, the addition of two 100 GHz amplifiers in each channel of the measurement system is expected to reduce the PM noise floor by up to 12 dB. An important component of this project is the successful construction of two 100 GHz Invar cavity stabilized Gunn oscillators, which are to be used in a dual-PLL PM noise measurement system. These oscillators have been phase-locked to 10 GHz low-noise reference oscillators that use high-Q sapphire-loaded cavities and are referred to as SLCO.

While we have achieved phase lock of the 100 GHz Gunn oscillators to the SLCO, the Gunn oscillator's electronic frequency control bandwidth must be increased by a factor of 3 to improve its PM noise. Future work involves increasing the slew-rate (bandwidth) of the frequency control, which should permit reduction of reference noise to achieve the desired SLCO + divider-noise limit.

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