PM Noise Measurement at W-Band

Archita Hati, Craig W. Nelson, and David A. Howe

***Abstract*—We report a high-performance 92 to 96 GHz cross-spectrum phase modulation (PM) noise measurement system. Utilizing this system, we measured residual PM noise of several amplifiers, mixers, and frequency multipliers. Data for the measurement system noise floor and the PM noise of W-band components are reported. These results can serve as a temporary benchmark because little or no information is available on the PM noise of components in this frequency range. In addition, we discuss an enhanced-performance frequency synthesizer that operates in the 92 to 96 GHz range. We achieved 5 to 10 dB improvement in the PM noise at 96 GHz compared with our previously designed synthesizer.**

I. Introduction

The migration to W-band frequencies (75 to 110 GHz) is central to the advancement of many applications, particularly satellite communications [1], radar for targeting and tracking purposes [2], imaging [3], [4], and vibrometry for concealed weapons/explosive detection [5]. The successful realization of these applications depends on the availability of low-PM-noise reference oscillators and other electronics at W-band. Obviously, as low-noise sources become available at higher carrier frequencies, more demand is put on the measurement system. Many of the traditional PM noise measurement techniques [6]–[10] are unavailable or may be difficult to implement at W-band and beyond. At these higher carrier frequencies, the PM noise characterizations using prototype measurement systems are often inconsistent, subject to inaccuracies, or limited by high measurement noise. There are only a few discussions in the literature on strategies and issues associated with state-of-the-art PM noise measurements [11]–[13] and low-noise synthesizer design [14], [15] at W-band.

Our earlier work [11], describes a W-band dual-channel PM noise measurement system. It was principally designed to measure amplifiers in pulsed mode with a duty cycle of 10% to 100% [continuous wave (CW)] at a given pulse repetition frequency. In this paper, we report improvement in the spectral purity (spurious response) of our previous measurement system noise floor. Using this improved system, we measured residual PM noise of various W-band components. We also report a new scheme for frequency synthesis in the 92 to 96 GHz frequency band that improves upon our previously reported design [11], represented as "synthesizer (scheme-1)" throughout this paper. In Section II, we briefly discuss the W-band dual-channel cross-spectrum PM noise measurement system and its noise floor under CW mode of operation. The residual PM noise performance of amplifiers, mixers, and multipliers is also reported in the same section. In Section III, we discuss the 92 to 96 GHz frequency synthesizer, its performance, and the limitations of synthesizer (scheme-1). Finally, the paper is summarized in Section IV.

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II. Residual PM Noise Measurement

The PM noise of devices must be characterized before implementing them in a master system. Frequently components with high noise are used for practical or cost reasons, although lower-noise components are available, thus affecting the overall performance of the system. The purpose of this section is to provide PM noise results of a few selective commercial components at W-band, because little or no information is available. We measured single-sideband (SSB) residual PM noise, $\mathcal{L}(f)$ of amplifiers, mixers, and multipliers at the 92 to 96 GHz carrier frequencies. Images of these components are shown in Fig. 1. They are all custom components from different manufacturers with performance optimized for the 92 to 96 GHz frequency band.

We began by measuring residual noise of selected amplifiers at 95 GHz using the set-up shown in Fig. 2(a). It is a conventional dual-channel cross-spectrum system [16], [17] for measuring PM noise of an amplifier [device under test (DUT)]. This system [image shown in Fig. 2(b)] is equipped to operate either in CW or pulsed mode. The full description and working principle of this measurement system can be found in our previous work [11]. Computing the cross-spectrum between two channels (CH1 and CH2) eliminates the effect of uncorrelated noise sources by $\sqrt{N}$, where N is the number of fast Fourier transform (FFT) averages used for cross-spectral analysis and reduces the noise floor of the measurement system to a level low enough that the noise of the DUT can be measured accurately. The PM noise floor of the measurement system is obtained by simply replacing the DUT with a waveguide with a delay equal to that of the DUT. The noise floor previously reported was swamped with power line 60 Hz and other spurious signals. We improved the spurious response of the noise floor by addressing the ground loop problems and by replacing the IF amplifiers used after the balanced mixers acting as phase detectors (PDs). The improved noise floor is shown in Fig. 3. Noise at offsets far from the carrier is limited by low power to the

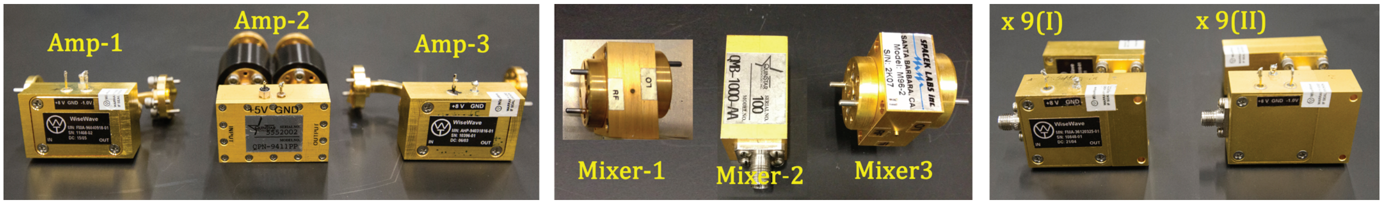

Fig. 1. Picture of commercial components used for PM noise measurement at W-band. These are custom components optimized for 92 to 96 GHz.

mixer caused by loss in the waveguides from the reference oscillator to the LO and RF ports. The noise floor can be further improved by increasing N, increasing the power to the mixer up to its maximum rating, and possibly by matching the delay more accurately in both paths. An I/Q modulator shown in Fig. 2(a) is implemented to calibrate the sensitivity of the PM noise measurement test set [18].

Following the characterization of the system noise, we compared the PM noise of two InP amplifiers (Amp-1 and Amp-3) with a third amplifier (Amp-2) whose type is not known. The gains of these amplifiers are 20, 16, and 17 dB, respectively, and the input power (P_{in}) for 1 dB compression is roughly 0 dBm for each amplifier. The PM noise of these amplifiers at the 1 dB compression point is shown in Fig. 4(a). Amp-2 has almost 10 dB higher flicker PM noise compared with Amp1 and Amp3. The broad noise structure above 100 kHz is an artifact of this amplifier and is not due to any contribution from the measurement system. Although Amp-1 and Amp-3 have very similar noise performance, Amp-3 shows multiple spurs above the 100 kHz offset. This is most likely from an internal switching dc-to-dc converter generating the gate voltage. Similar spurs are not visible in the PM noise plot of Amp-1, which has a linear voltage driving the gate.

The PM noise of Amp-1 was measured at three different input power levels and is shown in Fig. 4(b). It is clearly seen in Fig. 4(b) that the flicker PM noise of the amplifier at and below the 1 dB compression point is independent of the input power, commonly seen in most amplifiers of different technologies. However, the flicker noise is slightly lower when the amplifier is in a moderate compression regime. Under these power levels, the flicker frequency corner is above the 10 MHz offset frequency and is not observed because of insufficient frequency range of the FFT analyzer. The PM noise of the InP amplifier previously reported was affected by the high AM noise of the W-band source. Here, we overcome that problem by highly saturating the output of the W-band source with a high-power amplifier. Increasing the source power also helps saturate the PDs and reduce the AM-to-PM conversion.

An important component for any PM noise measurement system is the mixer used as the PD. To further characterize W-band components, we measured the residual PM noise of different commercially available GaAs balanced mixers at 95 GHz. A single-channel PM noise measurement system and an I/Q modulator for calibration were used. The block diagram of the test set and its image are shown in Figs. 5(a) and 5(b).

All three mixers have similar 1/f noise performance close to the carrier, as shown in Fig. 6, but far from the carrier, we see variation in noise resulting from different LO and RF power levels. The PM noise of Mixer-3 is evaluated when configured in channel-2 (CH2) of the cross-spectrum measurement system as shown in Fig. 2(a) without the DUT. Mixer-3 shows higher noise at offsets far from the carrier. This is because the power at the LO and RF ports was much less compared with the other two mixers because of the 7 to 10 dB loss in the waveguides from the reference oscillator to the PDs. Both mixers act-

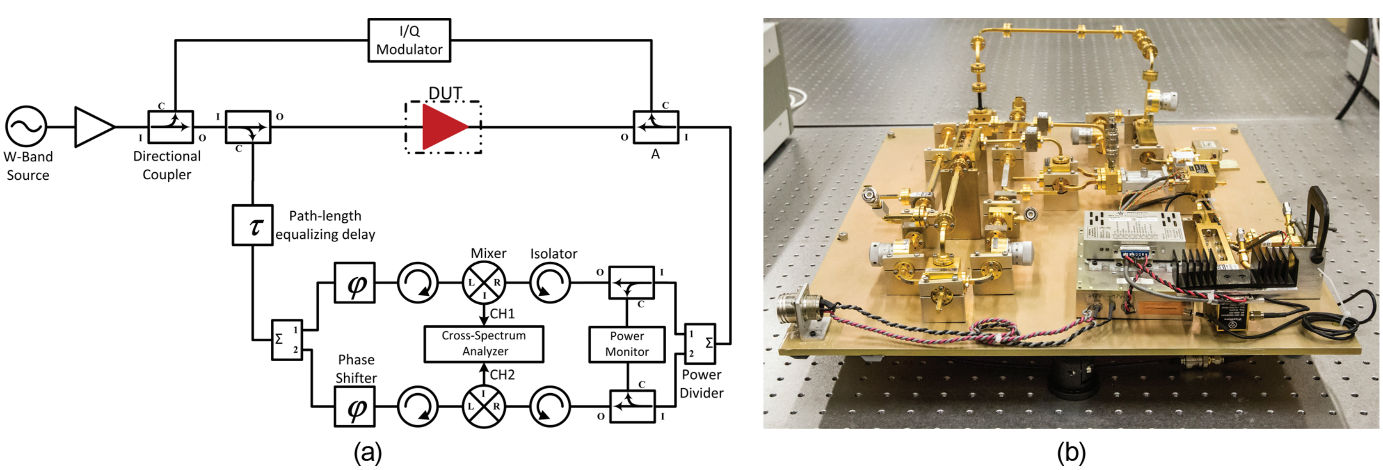

Fig. 2. (a) Block diagram of a two-channel cross-spectrum PM noise measurement system. The residual PM noise of an amplifier (DUT) is measured with the configuration shown. An I/Q modulator calibrates the sensitivity of the measurement system. (b) Image of the experimental setup.

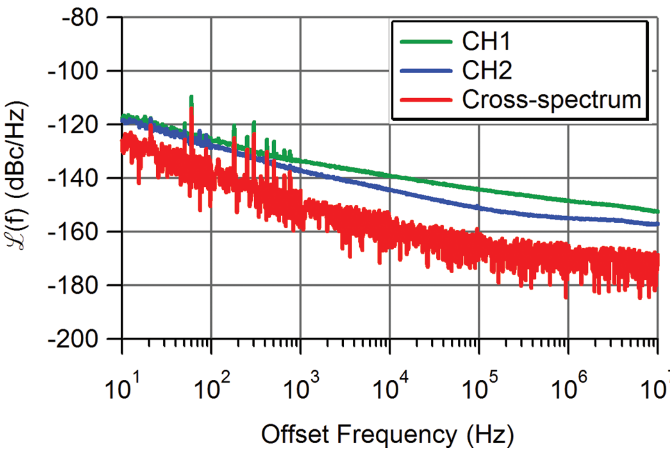

Fig. 3. PM noise floor of the W-band (92 to 96 GHz) measurement system. The number of FFT averages, N, chosen for each decade of frequency span (the first decade is 10 Hz to 100 Hz) are respectively 750, 1000, 2000, 2000, 2000, and 2000.

ing as PDs in CH1 and CH2 of Fig. 2(a) are the same type (identical manufacturer and model number) as Mixer-3.

In the next section, we will discuss a frequency synthesis scheme for which a frequency multiplier is an integral building block. Before implementing the synthesizer, we tested the noise performance of three GaAs multipliers, two ×9 (I and II) and one ×10 for an input frequency of 10 GHz. The test set-up is very similar to the mixer noise measurement. A pair (identical manufacturer and model number) of ×9 or ×10 multipliers are introduced as shown in Fig. 7. This configuration gives the PM noise for a pair of multipliers instead of a single multiplier. The PM noise of these multipliers are shown in Fig. 8, where it can be seen that the noise of ×9 (I and II) multipliers is almost 10 dB lower than the ×10 multiplier. Again for ×9(I), there are spurs above the 100 kHz offset. As discussed earlier, this is most likely from the switching dc-to-dc converter that is inside the multiplier packages for negative bias. By replacing the switching gate voltage with a linear power supply, the spurs in the ×9(II) were completely removed.

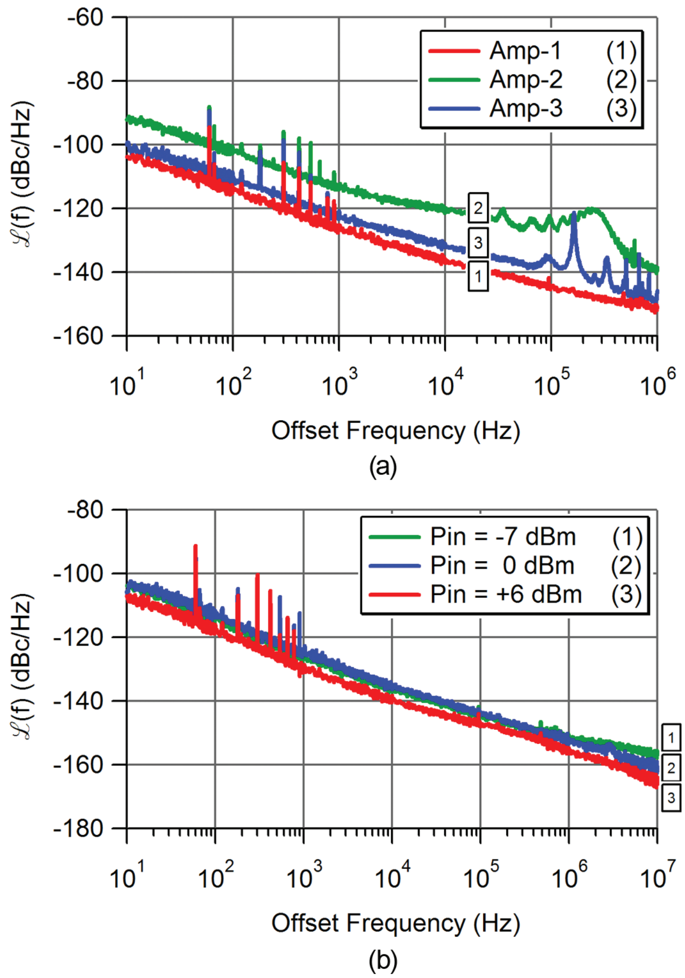

Fig. 4. (a) PM noise of a sample of commercial amplifiers operating at the 1 dB compression point ($P_{\text{in}} = 0$ dBm) at a carrier frequency of 95 GHz. (b) PM noise of InP amplifier (Amp-1) for three different carrier powers at 95 GHz.

These wide variations in the noise performance from one device to another indicate that it is crucial to identify the right components for implementing a low-noise system.

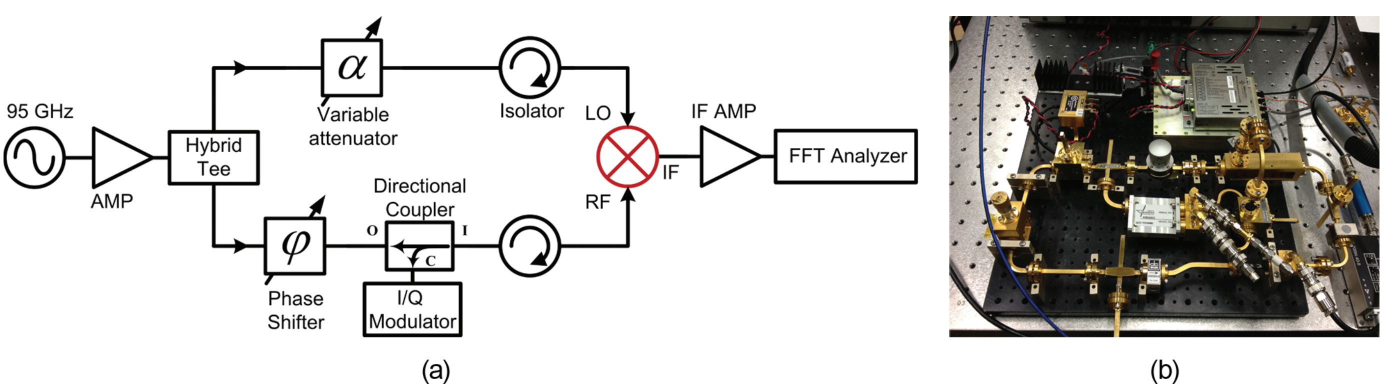

Fig. 5. (a) Block diagram of a single-channel PM noise measurement system for evaluating mixers. An I/Q modulator was used for determining the PM noise sensitivity of the measurement system. (b) Image of the experimental setup.

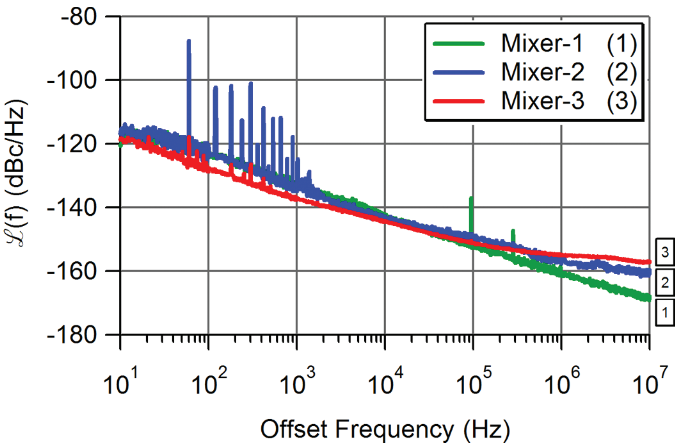

Fig. 6. PM noise of a sample of commercial mixers at 95 GHz.

III. Low-PM-Noise 92 to 96 GHz Frequency Synthesizer

The schematic diagram of a phase-locked 92 to 96 GHz frequency synthesizer is shown in Fig. 9. It consists of a W-band Gunn oscillator, a 10-GHz NIST cavity-stabilized oscillator (CSO) [19], a ×9 multiplier, a 100-MHz quartz crystal oscillator, a low-noise 2.1 to 6.1 GHz synthesizer, and phase locked loops (PLLs). The W-band signal is derived from a Gunn oscillator whose free-running PM noise at 94 GHz is equal to $[+80 - 10\log_{10}(f^3)]$ dBc/Hz. This oscillator utilizes high-performance GaAs and InP Gunn diode technology. A two-tiered phase lock system is used to extract the best noise from the 100 MHz, 10 GHz, and 92 to 96 GHz oscillators. The 10 GHz signal from the CSO, which is locked to a 100-MHz crystal oscillator, is multiplied by 9 and mixed with the 92 to 96 GHz signal from the Gunn oscillator to generate the 2 to 6 GHz intermediate frequency (IF). A 2.1 to 6.1 GHz signal from a low-noise synthesizer, also referenced to the same 100-MHz oscillator, is mixed with the IF to produce a 100 MHz beat signal. This beat signal is phase compared with the 100-MHz reference oscillator generating an error signal for the Gunn oscillator PLL. The current system provides lower phase-noise frequency synthesis compared with scheme-1 and allows for tuning with sub-hertz resolution through the 2.1 to 6.1 GHz synthesizer set point. In contrast, the 2.1 to 6.1 GHz signal in scheme-1 was generated with a noisier YIG-tuned multiplier that could only produce tuning of 100 MHz steps between 92 and 96 GHz.

The PM noise of the 92 to 96 GHz synthesizer is measured using a single-channel two-oscillator method [8]. Fig. 10 shows the PM noise of a locked Gunn oscillator at different frequencies. Unlike scheme-1, the noise at all frequencies between 92 and 96 GHz is almost equal. Additionally, at offsets higher than 1 kHz, the residual noise of the ×9 (I) multiplier adds noise to the 90 GHz signal and dominates the overall noise of the 92 to 96 GHz synthesized signals.

A PM noise comparison at 96 GHz of our improved performance synthesizer (scheme-2) and a YIG-tuned, multiplier-based synthesizer (scheme-1) is shown in Fig. 11. For scheme-1, the PM noise is almost 10 dB higher at the 1 kHz offset because of the larger noise contribution from the YIG-tuned multiplier at 6 GHz. Further, if we simply multiply a 10.666 GHz signal by 9 from a low-noise commercial signal generator (CSG) to generate 96 GHz, the noise of the synthesized signal will be higher than both scheme-1 and scheme-2, a comparison of which is also shown in Fig. 11.

IV. Conclusion

We presented an improved spectral purity dual-channel cross-spectrum PM noise measurement system that performs at W-band with a center frequency of 94 GHz. Utilizing this improved measurement system, we reported the residual PM noise performance of several amplifiers, mixers, and multipliers. Because little information is available about the PM noise of W-band components, the results presented here can serve as a temporary benchmark. We also discussed a 92 to 96 GHz frequency synthesis scheme and its noise performance. We achieved 5 to 10 dB improvement in the PM noise at 96 GHz compared with scheme-1. Although the signals at 10 GHz and 2.1 to 6.1 GHz have lower noise, ideal multiplication to 92 to 96 GHz was not achieved because of the dominating residual noise of the ×9 multiplier.

There are several emerging and existing technologies that generate ultra-low-phase-noise microwave signals ei-

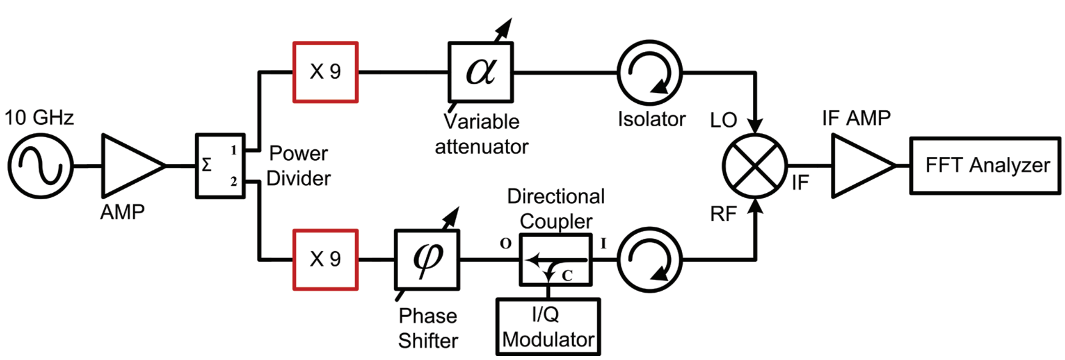

Fig. 7. Experimental noise measurement setup for a pair of multipliers.

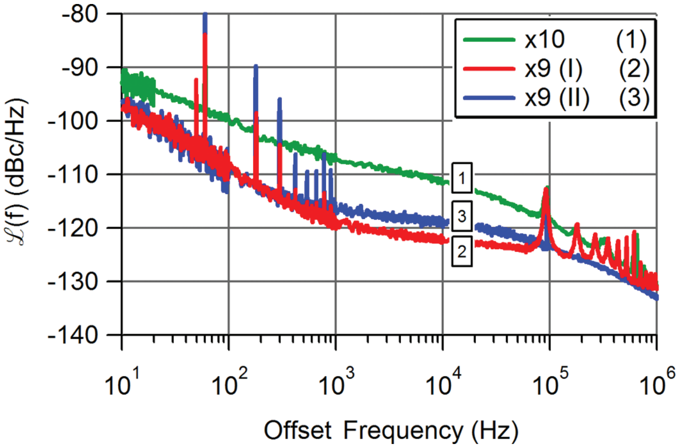

Fig. 8. Output referred PM noise of a pair of multipliers. Input frequency = 10 GHz. Output frequency = 90 GHz and 100 GHz. (Subtract 3 dB from plot for assumption of equal noise from each multiplier.)

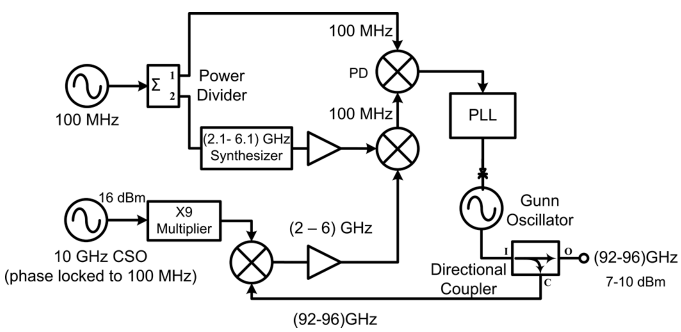

Fig. 9. Schematic diagram of the phase-locked 92 to 96 GHz synthesizer.

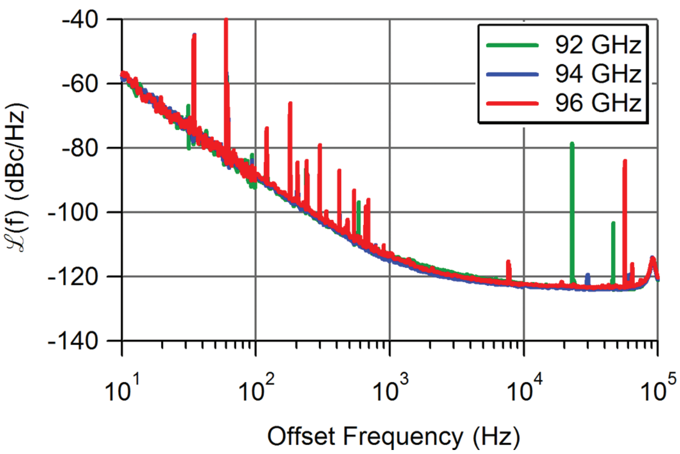

Fig. 10. PM noise of the synthesizer at different frequencies. Measured PM noise is combined noise of a pair of similar synthesizers. Noise of a single synthesizer is 0 to 3 dB better than shown.

ther from the optical-comb-based frequency division of a cavity-stabilized laser [20], [21], or from a cryo-cooled sapphire microwave oscillator [22]. Fig. 12 depicts the PM noise of these state-of-the-art signals scaled to 94 GHz. The results clearly indicate that ideal noise multiplication will be limited by the W-band multiplier. To achieve unperturbed high spectral purity from these potential sources, it is important to implement different schemes to

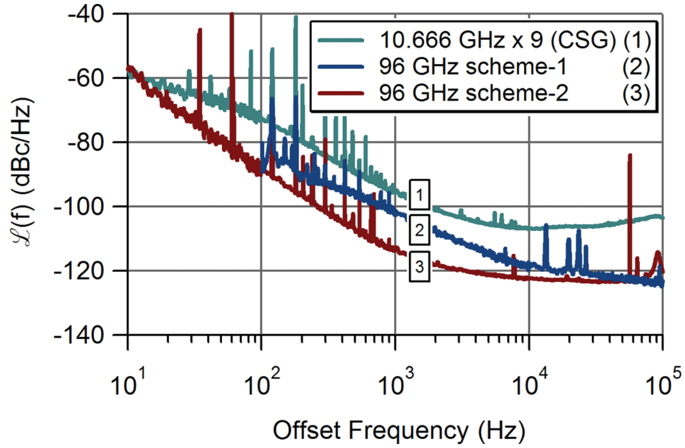

Fig. 11. PM noise comparison of synthesizer pairs at 96 GHz. CSG = commercial signal generator.

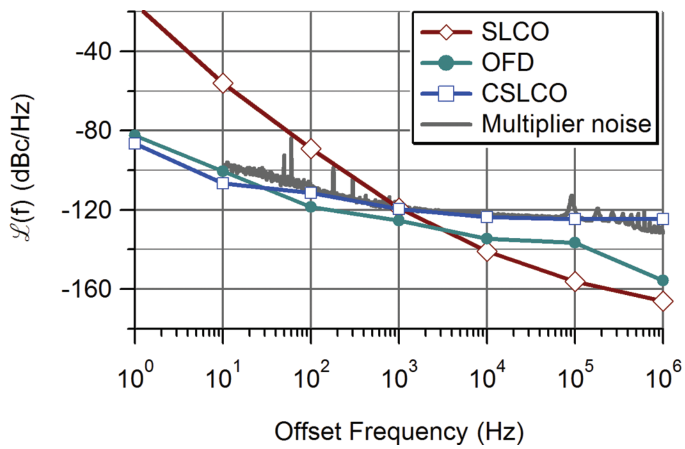

Fig. 12. PM noise of a pair of state-of-the-art signal sources scaled to 94 GHz and ×9 multiplier noise. SLCO = sapphire loaded cavity oscillator; OFD = optical frequency comb divider; CSLCO = cryogenic sapphire loaded cavity oscillator.

reduce either the multiplier noise or investigate whether a photonic approach will result in the best spectral purity.

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David A. Howe has been the leader of the Time and Frequency Metrology Group of the National Institute of Standards and Technology and the Physics Laboratory's Time and Frequency Division since 1999. His expertise includes spectral estimation, spectral purity and phase noise analysis of oscillators, accuracy evaluations of atomic standards, statistical theory, and clock-ensemble algorithms. In 1970, he was with the NIST (then NBS) Dissemination Research Section, where he coordinated the first lunar-ranging and spacecraft time-synchronization experiments. Starting in 1984, he led and implemented several global high-accuracy satellite-based two-way time-synchronization experiments with other national laboratories and was awarded the Commerce Department's Gold Medal. From 1994 to 1999, he worked as a statistical theorist for the Time Scale Section, which maintains UTC(NIST). He is the developer of the Total and TheoH variances used in high-accuracy estimation of long-term frequency stability, for which he won an NIST Bronze Medal and a second Bronze in 2012. He received the 2013 IEEE Cady Award. He has more than 140 publications and two patents in subjects related to precise frequency standards, timing, and synchronization.