Phase-Noise Measurement System for the Terahertz-Band

J. A. DeSalvo, A. Hati, C. Nelson, and D. A. Howe

***Abstract*—We present phase-noise measurements in support of terahertz electronics. By combining even-harmonic mixers with a 2.5 GHz frequency comb, we achieve a phase-noise measurement system in waveguide (WR1.5) by use of cross-spectral and digital phase-noise measurement techniques. At 670 GHz an upper bound of this system's noise floor is found to be −20, −40, and −60 dBc/Hz at 1, 100, and 10000 Hz offsets, respectively. In addition, a commercial, low-phase-noise, 670 GHz source is measured at offset frequencies from 0.1 Hz to 1 MHz.**

***Index Terms*—Frequency control, harmonic mixers, metrology, phase noise, submillimeter wave measurements.**

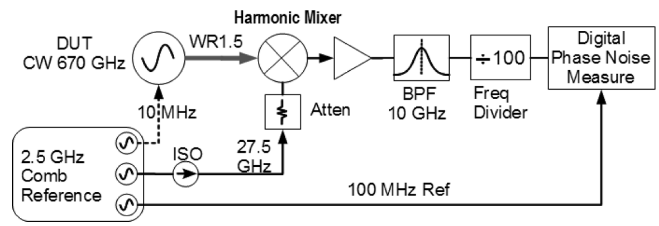

Fig. 1. Digital phase-noise measurement of a 670 GHz source. ISO: isolator, Atten: attenuator, BPF: band-pass filter.

I. Introduction

LOW-PHASE-NOISE continuous-wave (CW) signals at terahertz frequencies are important in molecular spectroscopy [1], [2], imaging [3]–[7], high-bandwidth-communications [8], and space-based radar [9]. Preserving phase stability is essential for these technologies to progress. Naturally, as very spectrally pure sources increase in frequency, more demand is put on the measurement system.

Many of the traditional phase-noise measurement systems are difficult to achieve for sources beyond 125 GHz [1], [10]–[12]. There are phase-noise measurement techniques found in the optical community that are implementable within the terahertz band, but most require significant investment for an extremely narrow usable frequency band [10], [13]–[15] or lack equivalent submillimeter wavelength technology [14], [16]. The delay-line frequency discriminator may soon show promise in the terahertz band [17]. One noteworthy phase-noise measurement was performed on a pair of multiplier chains targeting 1.3 THz, a rotational transition frequency of the molecular hydrogen ion, HD^+ [18]. Although perhaps not intended as a general purpose terahertz phase-noise measurement system, this impressive setup appears to be usable from 1.25 to 1.39 THz with the principle disadvantage being the cost and complexity of a cryogenic hot electron bolometer (HEB), achieving appropriate alignment and polarization of two terahertz sources, as well as a somewhat limited offset frequency range between 10 Hz and 10 kHz. Finally, due to an abundance of noisy sources at frequencies beyond the W-band, and the associated challenges of directly measuring phase-noise, the spectral purity is often characterized in current literature from the residual linewidth [19]–[21], which offers only indirect insight into the underlying noise processes of very spectrally pure sources [22]–[24].

The metrology community is motivated to develop terahertz phase-noise measurement capabilities in order to assure characterization of phase-noise for applications that would integrate terahertz components into usable products. NIST is developing phase-noise measurement systems that support 670 GHz, 850 GHz, and 1.05 THz[1]. In this document we present the first cross-spectral phase-noise measurement of a spectrally clean THz source. Our measurement system, implemented in WR1.5 waveguide (500–750 GHz), can easily be extended to WR1.0. We report an upper bound on the measurement system noise floor in addition to the measurement of a commercial, spectrally clean, 670 GHz source at offset frequencies from 0.1 Hz to 1 MHz.

II. Measurement System Description

A single-channel measurement system diagram is shown in Fig. 1. Although one might choose between several even harmonics of the harmonic mixer to combine with a chosen comb tooth, Fig. 1 elucidates a combination that measures a source at 670 GHz. The terahertz signal to be measured enters an even-harmonic mixer via WR1.5 waveguide, or optionally via a feedhorn. Ideally, this signal will provide a power greater than 10 μW in order to saturate the mixer and suppress AM noise. Aside from the terahertz-band mixer that down-converts to a convenient intermediate frequency (IF), the local oscillator's (LO) phase-noise sets the measurement noise floor. The harmonic mixer's LO port fully saturates when provided with 10 dBm of power between 20 to 40 GHz. To serve as our LO reference, we have designed a 2.5 GHz frequency comb with discrete "teeth" selectable via an yttrium iron garnet (YIG) filter out to 50 GHz. The YIG filter is followed by a low-phase-noise amplifier with a fixed 34 dB of gain and then attenuated as necessary in order to drive the harmonic mixer LO port with

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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[1]Frequencies correspond to the first three phases of the DARPA Terahertz Electronics program.

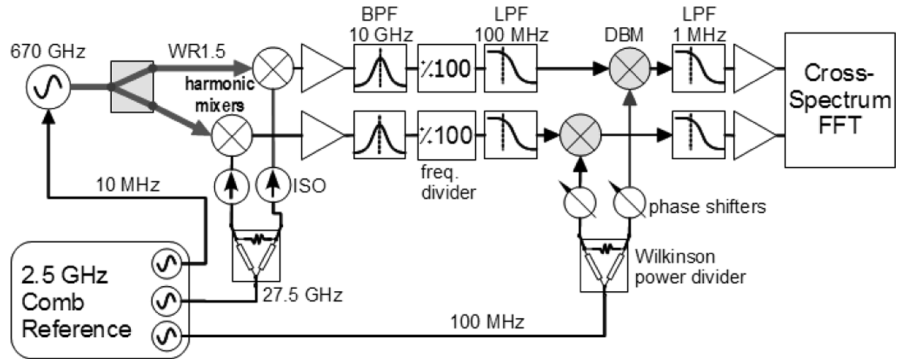

Fig. 2. Cross-spectral phase-noise measurement of a 670 GHz source. ISO: isolator, BPF: band-pass filter, LPF: low-pass filter, DBM: double-balanced mixer.

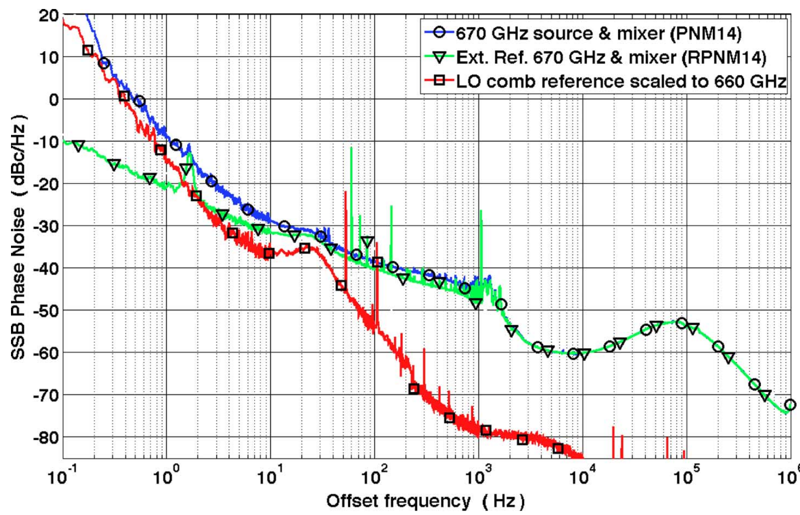

Fig. 3. Phase-noise measurements at 670 GHz.

9–10 dBm of power. This reference strategy provides adequate frequency agility, few spurs, and high power-per-harmonic number. The IF signal is then amplified, filtered, frequency-divided, and sampled with a commercial digital phase-noise measurement system.

The comb reference uses a 2.5 GHz step-recovery diode (SRD) to generate the frequency comb from a low-phase-noise 2.5 GHz dielectric resonator oscillator (DRO). The DRO is phase-locked to a 100 MHz quartz oscillator, which in turn is phase-locked to a 5 MHz quartz oscillator. Beyond the bandwidth of each phase-lock the controlled oscillator maintains lower phase-time power spectral density, $S_x(f)$, than the local reference, and vice versa, within the bandwidth of each phase-lock [25]. Recall that $S_x(f)$ is a frequency-normalized version of the one-sided power spectral density of the phase fluctuations, $S_\varphi(f)$ [26]

$$S_x(f) = \frac{1}{(2\pi\nu_0)^2} S_\varphi(f).$$

Here ν_0 represents the carrier frequency. We achieve the benefits of the lowest phase-time power spectral density of each oscillator in the chain by phase-locking at strategic bandwidths.

An optional cross-spectral phase-noise measurement configuration is shown in Fig. 2. Each channel is arranged similarly to the single-channel measurement except that we incorporate a 100 MHz to baseband conversion using double-balanced mixers as phase detectors. The quadrature condition is monitored from the mean voltage of the phase detectors. At a cost of twice the hardware complexity we gain the advantage that uncorrelated phase-noise generated by frequency conversion processes in the two synchronous channels will average out of the cross-spectral fast Fourier transform (FFT) at a rate of $N^{-0.5}$, where N is the number of averages. This allows us to establish a measurement floor below the residual phase-noise of a single channel. One limitation of the baseband conversion is that thermal drift will eventually shift the inputs to the phase detectors away from the calibrated quadrature setting. Because averaging out uncorrelated noise requires long averaging periods, close-to-carrier cross-spectral measurements are difficult with this open-loop baseband measurement.

III. Phase-Noise Measurements

Our single-channel measurement, designated PNM14 and shown in Fig. 3, yields the combined phase-noise from a 670 GHz source, the LO reference, and a WR1.5 harmonic mixer at offset frequencies from 0.1 Hz to 1 MHz. Later in this section, we demonstrate that neither the harmonic mixer nor the LO reference is making significant contribution to this result. We choose the comb tooth at 27.5 GHz and provide a net gain of 26 dB to drive the LO port at 10 dBm. We incur approximately 60 dB of conversion loss, producing a 10 GHz IF beat from the 24th mixer harmonic and the 670 GHz, continuous-wave (CW) signal at the RF port. Although we currently lack adequate power measurements for WR1.5, we believe the mixer to be saturated because the conversion loss is greater than anticipated. After amplification and filtering, we divide the IF frequency by 100. The resulting 100 MHz signal is digitally sampled and phase compared to the 100 MHz reference, which is phase-coherent to the comb synthesis chain below 10 kHz. By use of digital cross-spectrum techniques [27], [28] the noise from sampling and digitizing is reduced, resulting in a direct computation of the phase-noise.

By using a harmonic mixer in the first stage of frequency conversion, we deliver the source phase-noise to the 10 GHz signal of the IF port at the 670 GHz level. This 36.5 dB leveraging arm ensures that none of the components after the harmonic mixer will contribute significant added phase-noise. However, the phase-noise at the LO port will arrive at the IF port after being multiplied to the 24th harmonic. Thus the measurement floor of this system is dominated by the performance of the comb and harmonic mixer. Plotted with square markers in Fig. 3 is the phase-noise of the 27.5 GHz LO reference scaled up to 660 GHz, which constitutes the reference noise floor of the measurement system. The comb was characterized with three composite phase-noise measurement techniques to cover offsets from 10^{-2} to 10^{6} Hz. Direct digital phase-noise measurement techniques performed on a frequency divided comb tooth sufficed close-to-carrier. A loose-phase-lock loop measurement was implemented for offsets above 1 kHz; and, an optical delay-line phase-noise measurement [29] provided overlapping results between.

We are able to tighten the upper bound on the phase-noise of the mixer by externally locking the source to the common 10 MHz signal within our LO comb reference. This residual phase-noise measurement (RPNM14), shown with triangular markers in Fig. 3, represents the phase-noise of the harmonic mixer in addition to synthesis processes in the 670 GHz source that occur after the external phase-lock or beyond the phase-lock bandwidth, such as the multiplier chain. Between 0.1 Hz and 10 Hz, RPNM14 is below PNM14 and exhibits a flicker-phase-noise process, with a 1/f slope. It follows that PNM14 has little contribution from the harmonic mixer at offset frequencies below 10 Hz. While the source was externally locked, the digital phase-noise measurement was verified at baseband above 10 Hz offsets by use of double-balanced, quadrature mixing at 100 MHz and a single-sideband phase-gain calibration [30].

Week-to-week observations of PNM14 were at most $\pm 2.0\ \mathrm{dBc/Hz}$. These variations were noted at offset frequencies below 10 Hz and were likely dominated by environmental variations affecting the source. RPNM14 produced more consistent week-to-week observations, varying at most by ±0.5 dBc/Hz. The noise floor of the digital phase-noise measurement system is more than 60 dB below either measurement and has not been plotted in Fig. 3. The commercial digital phase-noise measurement system is self-calibrated to provide an accuracy of ±1 dBc/Hz.

In order to demonstrate that PNM14 had no contribution from the harmonic mixer at offsets above 10 Hz, we perform the baseband cross-spectrum PM noise measurement shown in Fig. 2. Uncorrelated harmonic mixer noise from the two channels will average out of the cross-spectral FFT. It was difficult to measure below offset frequencies of 10 Hz due to thermal drift of the quadrature condition. A single-sideband phase-gain calibration was again used. The resulting measurement, accurate to $\pm 2.0\ \mathrm{dBc/Hz}$, was practically identical to RPNM14 and demonstrated no decorrelation of the two channels. In combination with RPNM14, we conclude that the harmonic mixer does not contribute to PNM14; so, we have successfully measured the phase-noise of this 670 GHz source from 0.1 Hz to 1 MHz.

IV. Discussion

We note that the LO comb reference is only a few decibels below PNM14 for offsets below 1 Hz, as well as between 20–30 Hz, where the comb reference transitions to the 100 MHz cleanup oscillator. This is to be expected, because the 670 GHz source uses technology similar to that inherent in the reference. Although slight deflections occur due to the reference noise floor, the reference appears to be superior enough to conclude that, within a few decibels, PNM14 successfully measured this quality 670 GHz source combined with the harmonic mixer for offsets from 0.1 Hz to 1 MHz. Furthermore, our cross-spectral measurement and RPNM14 together demonstrate that the harmonic mixer makes little contribution to PNM14.

Between 0.1 and 10 Hz offsets, RPNM14 demonstrates a flicker-phase-noise process, with a $1/f$ slope, whereas the source shows a flicker-frequency process with slope of $1/f^3$. We can conjecture that the dip behavior at offsets above 1.0 kHz is due to a cleanup phase-locked loop (PLL) within the 670 GHz source, indicating that our measurement system has better performance than can be verified with this source.

V. Conclusions

We conclude that at 670 GHz our phase-noise measurement system achieves a noise floor of at most -10, -20, -40, and -60 dBc/Hz at 0.1, 1, 100, and 10000 Hz offsets, respectively. In addition, we have successfully measured a 670 GHz source in WR1.5 waveguide at offset frequencies from 0.1 Hz to 1 MHz. Our immediate plans include a residual phase-noise measurement of a WR1.5 harmonic mixer in order to tighten the upper bound of our measurement system's noise floor. Future work will extend the measurement range to higher carrier frequencies.

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