Integrated W-Band Measurement System Combining IMD, S-Parameters and Noise Figure Suitable for Coax, Waveguide and On-Wafer Test

Joel P. Dunsmore
Keysight Technologies
Santa Rosa, CA, USA
joel_dunsmore@keysight.com

Suren Singh
Keysight Technologies
Santa Rosa, CA, USA
Suren_Singh@keysight.com

***Abstract*—New commercial applications for mm-wave systems have driven the need for systems that can accurately and efficiently measure attributes of mm-wave amplifiers, including S-parameters, Two-Tone Intermodulation Distortion (IMD), and Noise Figure. Implicit in the system is automated control to seamlessly switch between measurement applications such as S-parameter (including gain compression measurements), IMD, and noise figure.**

Keywords—mm-wave, millimeter wave, noise figure, w-band

I. Introduction

The expansion of communications systems into mm-wave frequencies and the growing role of automotive radar has greatly increased the commercial use of radio spectrum in the W-band. Previously, W-band measurements were largely the province of industrial and academic research labs, and as such the convenience and cost of mm-wave test systems were secondary to the need to simply make the desired measurement. With the advent of advanced systems operating in the mm-wave band becoming commercialized, there is a need for a system that can combine multiple measurements into a single-system with a single connection. This is particularly true for the case of on-wafer testing, where the process of “touching down” on a die-site always carries the potential to damage the device bonding pad, so the number of touch-downs needs to minimum; ideally one.

While W-band noise measurements systems have been described in the past [1] we introduce a compact system, based on cold-source noise methods, that allows a single-connection multiple-measurement of all these attributes, and is suitable for on-wafer testing. This system utilizes the cold-noise method applied to mm-wave frequencies (up to 110 GHz) and novel in this system is removing the need for utilizing mm noise sources for the noise figure calibration, greatly reducing the system uncertainty. The system, based on a 4-port Vector

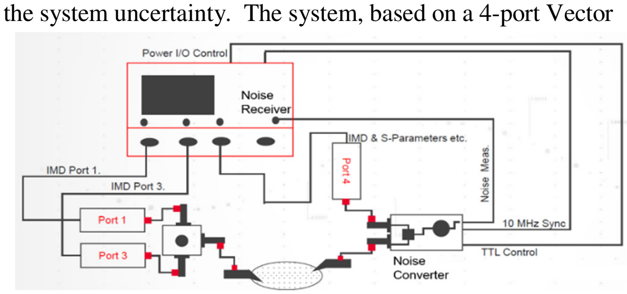

Figure 1: System Block Diagram

Network Analyser, with a built-in 50 GHz noise receiver, allows automated switching between measurement applications such as S-parameter (including gain compression measurements), IMD, and noise figure.

Calibration at mm-frequencies is performed using power-meter methods, traceable to the accuracy of the power meter used. Based on cold-source methods, no mm-wave noises are required or used in the calibration or measurement of the system. Additionally, extending this system for transistor noise parameter measurements is possible [2].

II. System Configuration

Figure 1 shows a block diagram of the measurement system configured for all measurements. The VNA used is from Keysight Technologies, model N5291A, with the option 029 (internal 54 GHz noise receiver), and includes three mm-extension heads, and a mm-head controller unit. Also shown is a W-band noise down-converter module which includes an integrated W-band switch to route the output of the DUT either to the integrated low-noise down-converter or to the external mm-head. Port 1 of the VNA system is connected to the input of the DUT and is utilized to measure the gain, compression, and for measuring the noise figure using the cold source method. Port 2 (which includes a 54 GHz dedicated noise receiver) is connected to the output of the W-band down converter. This receiver has an internal noise figure (as measured at the test port) in the range of 9-12 dB. An important part of the system design is ensuring the DUT noise as presented at the output of the W-band converter is at or above the Port 2 noise receiver.

Port 3 of the VNA system is used as a second source for IMD measurements and is combined with the Port 1 source to generate the two-tone signals at the input of the DUT. Port 4 of the system is used as the output port for measuring S-parameters (with full correction), as an IMD Spectrum Analyzer receiver, and for gain-compression measurements. Further, this version of VNA includes the capability of performing as a spectrum analyzer, and port 4 can be used to look for spurious oscillations over in the W-band at the output of the amplifier. Similarly, Port 2 of the VNA can be re-configured to also be a spectrum analyzer, up to 70 GHz, and can identify any system spurious created in the mm-wave down-converter. This can be useful to identify if spikes in the measured noise figure are from the DUT or from internally generated spurs.

The details of the W-band down-converter are shown in Figure 2 The input of the converter is directly connected to a waveguide switch, which either returns the signal to the port-4 test head of the VNA, or passes it through to a W-band downconverter, after an appropriate LNA. Also included is an electronic control of the waveguide switch, which allows the VNA to automatically switch between normal (S-parameter) mode and noise mode. The down-converter system includes a built-in 69 GHz local oscillator, derived from the 10 MHz output of the VNA. The output of the mixer is followed by a low-pass filter to remove LO feedthrough as well as the higher image out of the mixer.

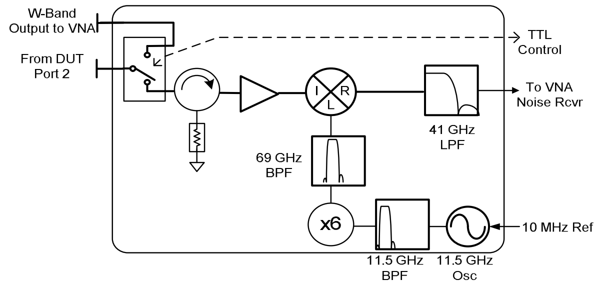

Figure 2: W-band Down-Converter

The test system can be mounted on a bench top (as shown in Figure 3). As shown, the system is configured using 1 mm-connectors between the DUT. The W-Band noise converter has a W-Band waveguide input, so in the case of a 1-mm coax DUT, a W-Band to 1-mm adapter is used. For the on-wafer case, the W-band converter may be mounted to the wafer prober. Ports 1 and 3 of the VNA feed to a combiner at the input of the DUT. It has a small size (similar to older style mm-heads), that makes it reasonable to mount it on directly to an on-wafer test system.

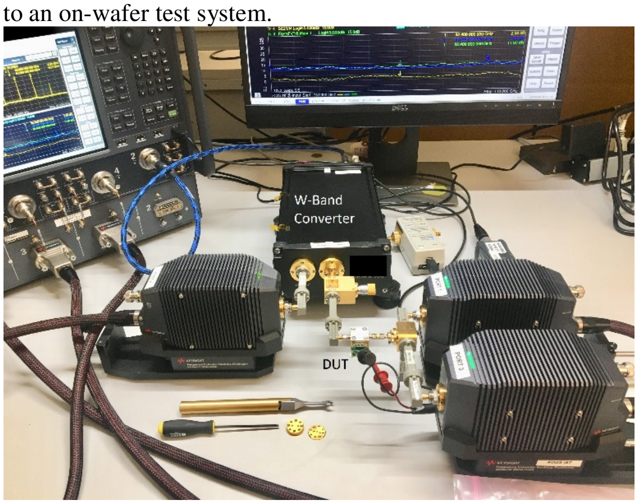

Figure 3: Photo of the Test System

III. System Calibration

The calibration of the test system utilizes a modified version of the built-in calibration feature of the VNA. In the first step, the VNA system is calibrated as a Scalar Converter Noise Figure measurement, where the noise figure and the gain of the W-band converter are measured and stored. The calibration consists of four steps:

1) Noise Reciver IF Calibration: The VNA Port 2 noise reciever is calibrated to measure noise power at the IF (output) frequency of the W-band converter. The typical method is to do a noise-parameter calibration using a hot/cold noise source (to characterize the gain-bandwidth product of the VNA Port 2 noise receiver) and a vector noise calibration where several standards of a mechancial cal kit, or more typically, an electronic calibraiton kit (Ecal) is used to perform noise pulling on the noise receiver (thus finding the noise parameters of the VNA noise receiver), as well as used to calibrate the Port 2 reflectometer (which is used to measure the S22 of the W-band converter to correct for any noise parameter effects of the VNA noise receiver).

2) Port 1 Power Calibration and S11 Calibration: A W-band power meter and a W-band cal kit are used to perform a match-corrected power calibraiton at the W-band frequencies of interest [3]. After this calibraiton, the reference receiver of Port 1 is calibrated to measure true incident-power applied to the DUT during the noise figure measurement.

3) Port 2 Power Calibration and S22 Calibration: A 1-mm coaxial power meter which operates at the over W-Band and IF (output) frequencies is use to calibrate the Port 2 VNA receiver, as well as a vector caliration of Port 2 in the VNA mode. In this way a match-corrected power calibration is obtained at Port 2 for the IF output frequency of the W-band converter.

4) Port 1 to Port 4 2-port S-parameter calibration: The caibration for S-parameters is performed between Ports 1 and 4, using typical S-parameter calibration methods. Further, a match-corrected power calibraiton may be performed between these ports for purposes of power measurements such as IMD measurements and gain compression. The power calibration at port 1 is also used in measuring the W-band converter gain.

IV. Measurement Method

The measurement method for W-band noise figure consists of measuring the noise power from the DUT, as well as the gain from the DUT, and computing the noise figure from these two values. From the definition of noise figure [3]

$$N_F \equiv N_{Factor} = \left(\frac{Signal_{Input} / Noise_{Input}}{Signal_{Output} / Noise_{Output}} \right) = \frac{(S/N)_I}{(S/N)_O} = \left(\frac{S_I}{S_O}\right) \cdot \left(\frac{N_O}{N_I}\right) \tag{1}$$

From which we can compute noise figure as

$$N_{Factor} = \left(\frac{1}{Gain}\right) \cdot \left(\frac{N_{Out}}{N_{In}}\right) = \frac{N_{Out}}{Gain \cdot N_{In}} = \frac{N_{Out\_Avail}}{G_{Avail} \cdot N_{In\_Avail}} \tag{2}$$

From this we can find the noise factor using more commonly used factors such as S21 and incident noise such that

$$G_A = \frac{\left(1-|\Gamma_S|^2\right)|S_{21}|^2}{|1-\Gamma_S S_{11}|^2 \left(1-|\Gamma_2|^2\right)} = \tag{3}$$

$$where \quad \Gamma_2 = \left(S_{22} + \frac{S_{21} S_{12} \Gamma_S}{1 - S_{11}\Gamma_S} \right)$$

And

$$N_{In\_Avail} = N_a = kTB, N_{Out\_Avail} = \frac{N_{IncidentOut}}{\left(1-|\Gamma_2|^2\right)} \tag{4}$$

From which we can compute noise factor as

$$N_F = \frac{N_{IncidentOut}}{\left(\frac{\left(1-|\Gamma_S|^2\right)|S_{21}|^2}{|1-\Gamma_S S_{11}|^2} \right) \cdot (kTB)} \tag{5}$$

And for the most common case of noise figure, defined as the noise figure for a matched input, where Zin=50 ohms, and $\Gamma_s = 0$, the noise figure becomes simply

$$N_F = \frac{N_{IncidentOut}}{\left(|S_{21}|^2\right)\cdot(kTB)} \tag{6}$$

In the W-band noise figure system, the noise figure of the DUT is not measured directly; instead the noise figure of the entire chain, or system, comprised of the DUT plus the W-band converter is measured. In addition, a one-time measurement of the W-band converter by itself is required. From this we can compute the noise figure of the DUT by itself, utilizing the Friis equation. In this system we are looking for the noise figure of only the DUT, $F_{1,}$ which we compute as

$$F_{DUT} = F_{Sys} + \frac{F_{WBC} - 1}{G_{DUT}} \tag{7}$$

Where F_{WBC} is the noise figure of the W-band converter. To perform the measurement on the DUT, a first measurement of the W-band converter is performed and saved as a reference trace. The measurement is made from characterizing the output noise of the converter and the gain of the converter (called SC21 to indicate it is converter gain), which is also saved as a reference trace. This one-time measurement can be considered a kind of second-tier calibration. After this, the noise figure of the W-band DUT is computed from equation, by computing the gain of the system divided by the reference gain of the W-band converter, and the noise figure of the W-band converter, and applying equation (7) as

$$F_{DUT} = F_{Sys} + (F_{WBC} - 1) / \left(|SC21_{Sys}| / |SC21_{WBC}|\right)^2 \tag{8}$$

in the built-in equation editor function of the VNA. This was done for a wide-band mm-wave module, as shown in Figure 4, lower window.

Here we see one trace is overall system noise figure, F_{SYS}, labeled as SYSNF, one trace for the $SC21_{Sys}$, labeled SC21/M, and a trace for DUT NF, labeled DUTNF using equation (8).

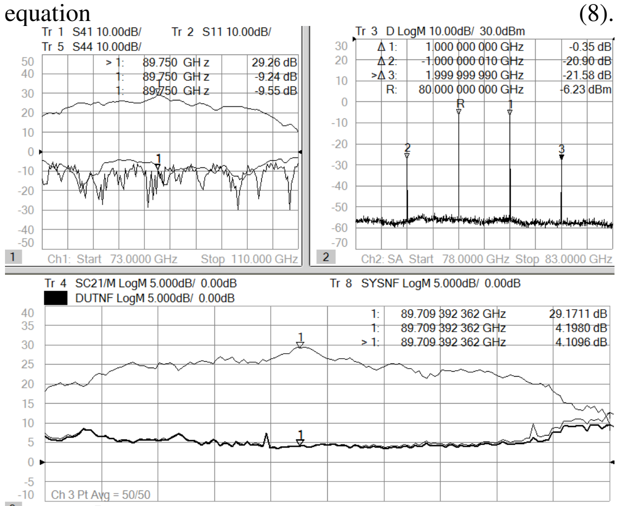

Figure 4: S-Parameter, IMD and Noise Figure

V. Multiple Measurement Scenario

A. S-Parameter Measurements

One key aspect of this solution is the ability to make multiple measurements with a single connection. The noise figure measurement can include the gain, but the gain is simple ratio of the input system SC21 and the W-band converter SC21, and so this ratio does not include mismatch effects between the DUT and W-band converter. For noise figure, this doesn't matter because the mismatch from the DUT output to the W-band converter input is common to the noise power and the SC21 measurement. The SC21 measurement method does correct for input mismatch between port 1 of the VNA and the DUT or system being measured. However, it is typical to want to measure the 2-port S-parameters of the DUT as normally defined, and this can be accomplished using the switched path to port 4 of the system. A normal 2-port calibration is used and the key S-parameters can be measured as illustrated in Figure 4, upper left. Note the S21 trace is a quite a bit smoother than in the NF gain, due to 2-port calibration.

B. Gain Compression Measurements

The P1dB or gain compression point is generally not a key specification, but it is desired to know what the value is to ensure the LNA is used well away from its compression point. The VNA system, utilizing a match-corrected power calibration, can do single-frequency power sweeps, but can also provide the 1 dB compression point as a function of swept frequency, utilizing a kind-of 2-dimenstional sweep.
For this amplifier the worst-case point is near 90 GHz with an input P1dB of -32 dBm. For noise measurements we should back off at least 10 to 15 dB from this value.

C. IMD Measurements

It is common for the intermodulation (IMD) performance of an LNA to be specified, and it can be directly measured in this case using the second source for the VNA to create a second tone, which is combined before the input of the LNA, as illustrated in Figure 1. Here the two sources are set to be equal at the output of the DUT and the IM products are measured utilizing the built-in spectrum analyzer function and the marker values to generate the IMD value in dBc. This is illustrated in Figure 4, upper right. Here the power in each input tone is set to about -35 dBm, just below the 1 dB compression point. We see from the markers the IMD level is about -20 dBc. The input signals are equalized at the output to less than 0.35 dB offset.

D. Single-Connection Multiple-Measurement

Due to the integrated nature of the system, as well as automated control of the W-band converter, all of these measurements can be combined into a single instrument state that can be triggered on a per-device basis. As such an on-wafer test system can simply move the probes to a new LNA and trigger a system sweep, to generate a complete data acquisition cycle.

VI. Measurement Consderations

Making noise figure measurements in the W-band region brings some special challenges. Foremost is creating a system than can measure relatively low noise powers in the W-band region. For this purpose, a W-band converter system was designed. The first element is an input switch that allows the W-band converter to be bypassed for measurements such as S-parameters, IMD and gain compression, by routing one leg of the switch from the input mm-head to a second mm-head. The other leg of the switch is routed to the W-band down converter. Because mm-wave converters often have relatively high conversion loss, an input amplifier (W-band LNA) is inserted between the switch and W-band down converter. The LNA is preceded by an isolator as the input match to the LNA is not very good (on the order of -5 dBc) and this would cause some additional uncertainty due to mismatch with the DUT output. The W-band system provides a built-in hi-pass function so no filtering is needed after the LNA.

A typical noise converter system uses a swept Local Oscillator to a narrow-band noise receiver. But cost and complexity rules out a swept LO in this system, and we can make use of the relatively wide-band noise receiver built into the VNA. So in this case we use a 69 GHz local oscillator to derive the W-band mixer. The LO is derived from a phase locked 11.5 GHz oscillator which is multiplied by six-times to get to 69 GHz. The ll.5 GHz is locked to the internal 10 MHz reference. The ll.5 GHz signal must also be filtered to ensure a clean signal to the 6x multiplier.

A. *Noise Considerations*

The gain of the input LNA must be carefully managed, as mm-wave LNAs do not have very large P1dB (approximately -2 dBm output) and the system must have at least 15 dB back-off from P1dB. The LNA in this case has a gain on the order to 20-28 dB, and an input noise figure of about 4 dB. The input isolation has about 1 dB of loss and the input switch has about 5 dB of loss. Since the only active device is the LNA, it is the only device that adds excess noise above the loss factor. The narrow-band filter from the LO to the mixer input is necessary to prevent LO broadband noise from converting to the IF band in the mixer. The bandwidth of the filter is 3 GHz, meaning it rejects noise offset more than about 1.5 GHz from the LO, thus it does not mix into the IF output frequencies.

B. *Power Considerations*

The output power of the first stage LNA is quite limited, to about -2 dBm P1 dB. At maximum gain, this means the input power to the LNA is about -30 dBm at P1 dB, and through the switch (at the input of the W-band converter) the P1 dB is about -35 dBm. For reasonable noise figure measurements, the compression should be held to less than 0.1 dB, which means about a 10 dB back-off from P1 dB, so the maximum input to the W-band converter is -45 dBm. For an example test DUT with 20 dB gain, the input power must be set to no higher than -65 dBm, which is low enough to start having noise-effects on the SC21 measurements (noisy measurement of the input power due to the low level).

For amplifiers that have gain on the order of 30 dB, we run into additional problems of compression of the W-band converter and compression of the VNA low-noise receiver (which has a maximum of about -30 dB excess noise input power): the broadband noise at the output of the test DUT can itself cause compression of the W-band converter. Consider a full-band W-band LNA, with 30 dB gain and a 5 dB noise figure. The excess noise density at the output is 35 dBm/Hz above kTB. Over the 40 GHz BW of the amplifier the integrated noise power is on the order of -33 dBm, above our maximum input of -45 dBm to avoid any compression. In fact this level of broadband noise will place us near the P1dB point of the W-band converter LNA. In such a case an attenuator should be used between amplifier and the W-band converter (about 10 dB for this example). Most on-wafer devices will not have such high gain but packaged devices may, as the device in the previous figures shows. We use a rotary variable attenuator on the input to allow flexibility for high gain devices (visible after the DUT in the waveguide path before the W-band converter, in Figure 3). To remove the effects of the attenuator, the DUT is removed and the attenuator is set to a desired value. The S2P file is measured of the resulting setting and saved, then de-embedded from port 2, removing the attenuator effects on S-parameter and IMD channels. For the noise figure channel, the gain and noise power are reduced equally, and so the attenuator does not affect the noise figure to the first order. The reference trace for the converter SC21 and converter noise figure are updated with the attenuator in-place before the DUT is added.

A final detail about calibration: the current method for calibrating the noise figure requires a path from port 1 to the VNA port 2 (bypassing the W-band converter) which will pass both the W-band frequencies and the IF output frequencies of the W-band converter. In this case the IMD combiner must be removed for the calibration step, and then must be measured in the W-band so its loss can be de-embedded from the noise figure measurements. In practice, adding the combiner can degrade the raw source match and cause some additional ripple in the noise figure measurement due to noise parameter effects. Adding a tuner before the DUT port 1 gives the potential to generate noise parameters.

VII. Uncertainty Considerations

Principal sources of uncertainty are the noise source ENR uncertainty used to characterize the VNA noise receiver in the IF range. This is on the order of 0.1 to 0.2 dB from low to high frequencies. The power meter uncertainty contributes to the error in characterizing the W-band converter loss, which has a second order effect on the noise figure, but also contributes to error in the system noise figure due to error in the system gain measurement, which directly effects the system noise figure. This error is on the order of 0.1 dB for the IF frequency range and 0.2 dB for the W-band frequency range. The final error is associated with the source match of the system, which if different from 50 ohms, can cause pulling of the noise receiver due to noise parameter effects. To fully understand this effect the noise parameters of the DUT must be known.

VIII. Refrenneces

[1] Vaha-Heikkila, M. Lahdes, M. Kantanen and J. Tuovinen, "On-wafer noise-parameter measurements at W-band," in IEEE Trans-actions on Microwave Theory and Techniques, vol. 51, no. 6, pp. 1621-1628, June 2003.

[2] P. J. Tasker, W. Reinert, J. Braunstein and M. Schlechtweg, "Direct Extraction of All Four Transistor Noise Parameters from a Single Noise Figure Measurement," *1992 22nd European Microwave Conference*, Helsinki, Finland, 1992, pp. 157-162..

[3] Dunsmore, Joel, “Handbook of Microwave Component Measurements”, John Wiley, 2012.