Broadband network analysis over 70 kHz to 220 GHz

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[Summary] Broadband network analysis measurements are increasingly needed to support device model development for 6G and other millimeter-wave applications. Not only must the operating bands of interest be measured (and harmonics), but data from much wider ranges is critical to verify and create models at the device and subsystem level with confidence. Making this measurement process easier would be the ability to collect data with a single probe touch-down or connection. Such a system operating over 70 kHz to 220 GHz has been developed and the operating principles, behaviors and measurement observations of that system will be discussed in this paper.

1 Introduction

Millimeter-wave applications continue to expand with imaging, point-to-point communications, local identification and 6G proposals among those currently being discussed.[e.g., 1) to 5)]. Certainly banded measurements in the region of operation will be required (network analysis, spectrum measurements, etc.) and one could argue that broadband measurement systems allow one to study devices and systems for different applications. Beyond that reason, however, are other issues that make broadband analysis even more important.

Many applications are over-the-air and hence there are emissions limits to consider so data at harmonic frequencies are often needed [e.g., 5)]. Further, the stability of many elements of subsystems may need to be evaluated out-of-band so that spurious emissions do not result (and may be connected to in-band performance degradation).

Central to the design of systems for mm-wave applications are device and subsystem models that must be accurate over different bias ranges, temperature conditions, signal composition and other variables. Important to the validation of those models is often an assessment of physicality which usually involves behaviors over wide frequency ranges including those well beyond the frequency range of the application [e.g., 6) to 8)]. Also, the devices and elements may be employed in different parts of the final system (e.g. RF and IF sides of the transceiver) so the behavior may be needed to be understood over a very wide range for purely practical reasons.

Assuming broadband data is needed, a conventional approach may be to use multiple banded instruments (or banded configurations using different mm-wave modules) and combining the data. This approach has several complications:

- Setup time can be significant (particularly in on-wafer measurements) so multiple changes in the configuration can greatly increase measurement time and the chances for configuration errors.
- In on-wafer mm-wave characterization, the pads used for probe contact have a limited lifetime. Already this can present a challenge when the characterization must be done at multiple temperatures (requiring multiple probe touch-downs). If multiple test configurations are required as well (and additional probe touch-downs), the test sequence may not be able to complete before the pads are worn out.
- The data in different bands will typically have different uncertainties (and different uncertainty mechanisms) and require different calibrations. It is thus not unusual for there to be discontinuities in data between bands. Rationalizing these differences and adjusting models to compensate can be complicated.

In view of these issues, a single-connection broadband measurement system that covers as much frequency range as possible could be helpful in characterization and verification tasks related to these burgeoning millimeter-wave applications. A vector network analyzer (VNA) system covering 70 kHz to 220 GHz (operational over 40 kHz to 226 GHz) has been developed for this purpose and has a single RF interface optimized for direct connection to on-wafer probes with adapters designed to link to coaxial and waveguide media as well. Section 2 of this paper will cover some of the measurement requirements believed to be needed in this space. Section 3 will discuss some design approaches taken for the measurement system and their implications. Section 4 will survey the instrument performance and how it can be used for diverse measurement needs.

2 Measurement requirements

Many performance attributes are universal to all of network analysis but the broadband characterization realm will emphasize certain parameters over others. As an example, absolute dynamic range (as might be needed to better measure a filter stopband) may be less useful for on-wafer characterization since probe-to-probe leakage can be very large at mm-wave frequencies and will dominate.

The fine grain quality of the S-parameter data can be quite important since de-embedding, which is needed to move the reference planes from the probe tips to the device proper, will tend to accentuate any problems. Thus measurement stability/drift and trace noise can be important variables[e.g., 9) to 10)].

Isolated transistor measurements (and certain low noise amplifier blocks) at mm-wave typically require very low drive levels to avoid DUT compression so wide power control range is important[11)]. Some banded mm-wave VNA structures have no active power control capabilities and the nominal power may not even be flat. This can lead to particularly distorted results if operating at the edge of linearity. The measurement of an LNA is shown in Figure 1 with an unflattened drive scenario as well as with a leveled VNA system set up for driving the device linearly. The unflattened system had higher drive levels at the extreme frequencies in the band which led to more DUT compression.

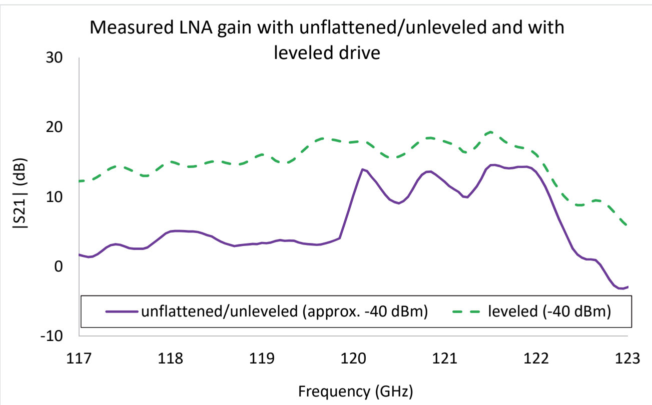

Figure 1 The effects of an unflattened/unleveled stimulus on a mm-wave LNA measurement can be substantial. Isolated transistor measurements can be more affected.

If quasi-linear characterization is needed (AM/AM, AM/PM, intermodulation distortion, etc.), then the absolute power accuracy at those levels is also of heightened interest. Since the drive levels may be low, the noise floor performance of the instrument may also play a significant role.

As the DUT output powers increase, the instrument's receiver linearity becomes increasingly relevant as distortions there are very difficult to calibrate. This linearity metric may be expressed in terms of a compression point or a third order intermodulation intercept point.

Beyond simple S-parameter measurements and their quasi-linear analogs and intermodulation distortion, there are other measurement requirements for these mm-wave applications. These may include true differential drive for balanced devices operating quasi-linearly or nonlinearly. Mixer or converter measurements and measurements of multipliers are also often needed. These requirements fall more into the 'functionality' category rather than being governed by numerical parameters but are still important.

3 Design Considerations

There are many different ways one could architect a broadband network analysis system and, since no single multiplier nor receiver can cover the entire frequency range, a central question is multiplexing. Conceivably, one could switch in different receivers and multipliers but, at the higher mm-wave frequencies, the insertion losses become prohibitive. Another approach is to use coupling structures and that method was used with the present instrument as well as with its lower frequency counterparts (Anritsu ME7838A/D/E)[12) to 13)]. The structure for a two port instrument is shown in Figure 2. A microwave VNA (Anritsu MS4647B 70 kHz to 70 GHz) provides direct stimulus up to about 50 GHz before the multiplexed multipliers in the mm-wave modules take over[14) to 15)]. The VNA receivers are used up to 30 GHz before the receivers in the mm-wave modules are used. The source and LO of the base VNA are used for functions within the base VNA and within the mm-wave modules.

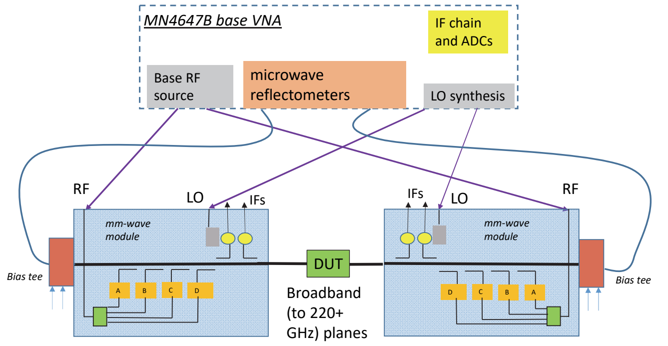

Figure 2 The block diagram of the 220+ GHz broadband VNA is shown here. Multiplexing is used on both stimulus (A-D are different multipliers for the different sub-bands) and receivers.

On the drive side, a set of increasingly high frequency multiplied paths couple onto the main signal math. This accomplishes several goals:

- Minimum excess insertion loss at the highest frequencies
- Simpler multiplier design
- Simpler control

The multipliers were all designed to have relatively soft power transfer curves (output power vs. input power) which allows for simpler power control over wider ranges while maintaining measurement stability. The different multiplier arms are labeled A-D in Figure 2 and correspond to x2, x3, x6 and x12, respectively. These structures are implemented with a hybrid of nonlinear transmission line (NLTL) structures and lumped diode designs. Detection for power control is done both at the IF level (for very wide power control ranges on non-frequency-converting measurements) and at the RF level (to support mixer, multiplier and other converting measurements)[15].

Another important attribute of the signal coupling onto the main path is that DC bias can be supplied as usual (from the rear connector on the module) without the need for extremely broadband bias tees. The main signal path of the module was designed to have very low DC resistance (few tenths of an ohm including RF connectors) so a Kelvin bias tee (allowing 4-point DC measurements) at the module rear encounters little measurement error.

The receiver side of the system is simpler since one coupler/receiver pair can cover 30 to 226 GHz. Lower frequencies are handled by the conventional base VNA (Anritsu MS4647B). An important attribute of this receiver is its linearity and is a high-LO version of the nonlinear transmission line (NLTL) structure[16] used in many Anritsu products (references needed here). The higher LO utilization allows for improved noise performance (fewer images) and fewer other spurious issues.

The IF signals from the mm-wave modules (used for RF signals in the 30 to 226 GHz range) are routed to the host VNA where they are switched into the VNAs common IF path when appropriate. Switching here is quite reasonable since the IF frequencies are not high (in the MHz range).

A final important part of the system design is the RF connection. While a conventional threaded coaxial connector can be considered, the center collet dimensions are small enough that axial and torsional forces on the inner conductor during a connection process would be severe enough to limit connector lifetime. Waveguide is really not an option in view of the broadband requirements. Instead, a coaxial-mode interface was designed that used a fairly conventional waveguide flange as the alignment mechanism. Thus the broadband nature is reserved while placing much less stress on the center conductor. Lower frequency coaxial connectors (1.85 mm, 1 mm, and 0.8 mm as examples) use split-finger female collets to maintain contact with the male pin. At the dimensions required for 220 GHz (coaxial outer conductor diameter is 0.6 mm), this split-fingered approach would have been too weak. Thus the male pin was instead split and applies spring force against the solid walls of the collet.

4 Performance levels

This section will examine some of the performance attributes of the system detailed in section 3. As discussed in earlier sections, stability of data and trace noise can be critical in modeling and characterization applications. A drift or stability test result is shown in Figure 3 for the system at an IF bandwidth of 100 Hz while the ambient temperature changes ±1C over a period of time. This level of deviation was within expectations.

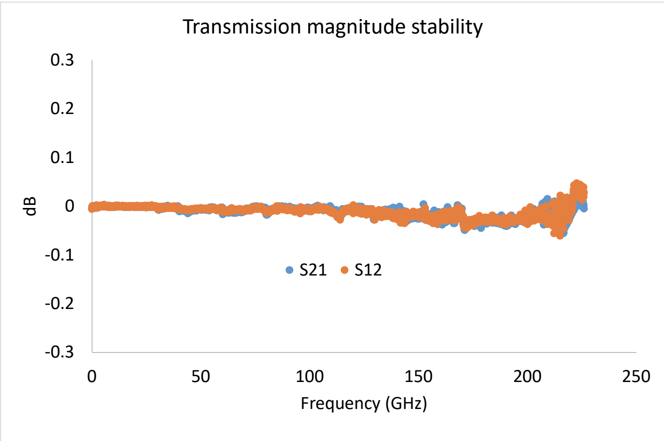

Figure 3　Stability and trace noise are important metrics of S-parameter data usability for modeling and characterization.

Calibrated measurements of standard artifacts is a common assessment tool. In coax, a Beatty line (a 25Ω section of line inserted in a 50Ω system) is a useful structure in that it is transmissive and predictable but poorly matched. This response of the new system (using flange to 0.8 mm adapters before the calibration reference plane) is compared against the results from lower frequency systems (125 GHz upper limit for the ME7838A and 145 GHz for the ME7838D) in Figure 4. The results agree within the expected uncertainties (to 0.4 dB at 145 GHz). A WR-5 waveguide attenuator was also used as a comparison device (using flange to WR-5 adapters on the present system) and these results are also shown in Figure 4. Data with a banded system at a subset of points is also shown and all of these results agree to within the expected uncertainties (to 0.7 dB at 220 GHz).

As discussed in a previous section, power control is quite important for device and subsystem characterization. Power sweeps of the present system at several frequencies between 50 and 226 GHz are shown in Figure 5. The receiver only has a coarse calibration so the absolute y-axis values must be interpreted carefully but the plot does indicate the available power control range and relative linearity. The receiver compression level was less than 0.1 dB at +5 dBm incident so receiver linearity should not be a limiting factor in most cases.

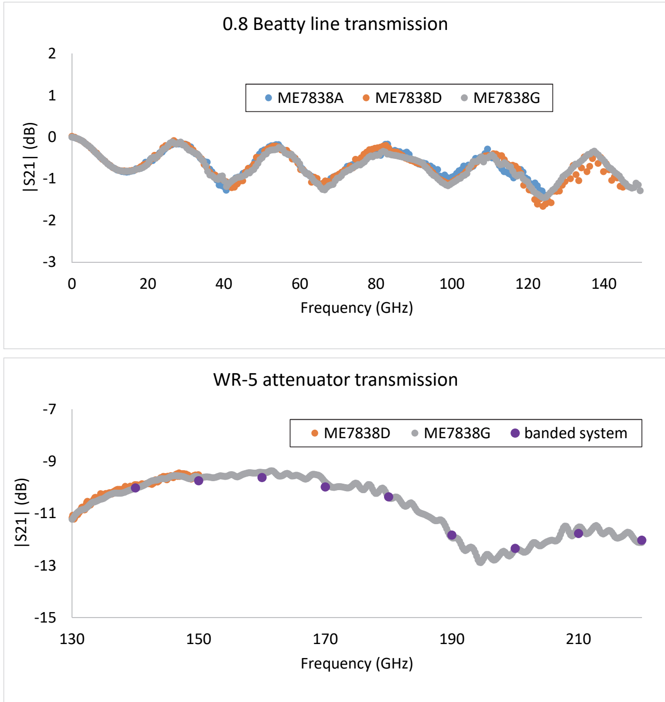

Figure 4　Calibrated measurements (using coaxial and waveguide calibration kits) of artifacts offer a basis of comparison between systems

When stimulus levels must be very low to avoid DUT compression, the instrument noise floor can be important, as mentioned earlier, in limiting uncertainty degradation. The noise floor of the present instrument is plotted in Figure 6. There is some roll-up at higher frequencies as front-end insertion loss becomes less negligible but the overall levels are still adequate for very good signal-to-noise ratios in device measurement.

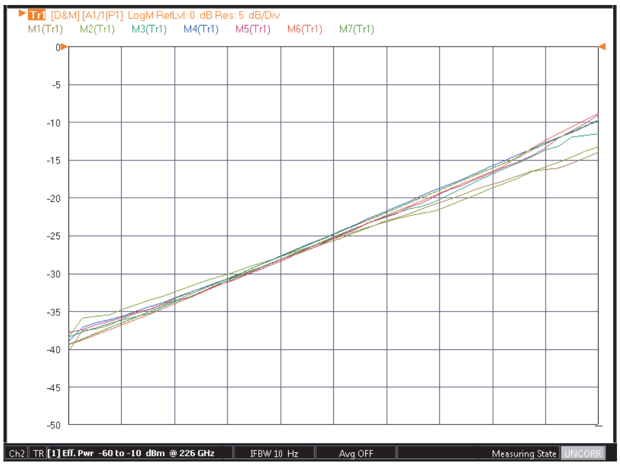

Figure 5　Power sweeps at a number of frequencies up to 226 GHz illustrate the power control range.

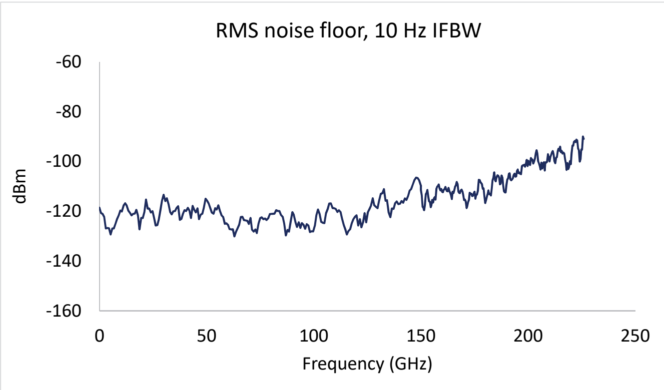

Figure 6 Instrument noise floor can be important when device stimulus levels must be very low.

When measuring active differential devices, the ability to apply a true differential signal or a dual signal of a well-known phase relationship can be useful[17]. The dual source drive capability of the instrument with phase synchronization allows this kind of measurement when in the four port configuration but the phase resolution for frequencies multiplied up to 220 GHz can be a challenge. A phase sweep (from 0 to 180 degrees) for this dual drive configuration is shown in Figure 7 at 220 GHz. While there is some trace noise in this measurement, it does appear that resolution is not a limiting factor.

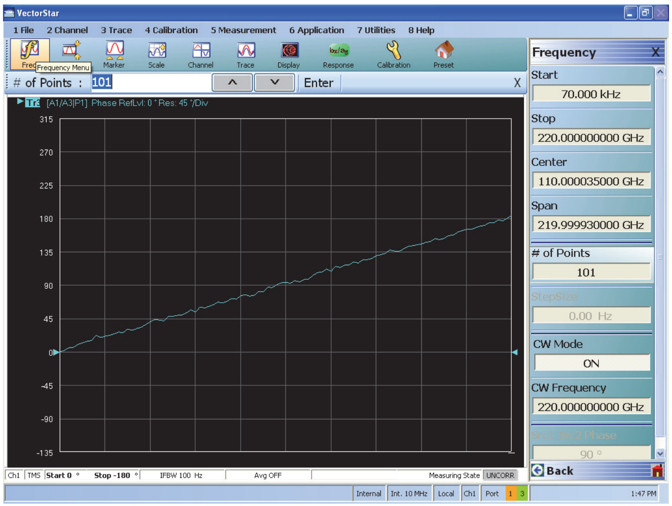

Figure 7 A dual-source drive with controlled phase relationship is needed for true differential drive and related measurement requirements.

Many mm-wave subsystems include frequency conversion of some variety and the ability to measure this type of structure is also important. In a multiplier measurement, for example, conversion efficiency, output power and power slope may all be of interest. In this case, output power of a tripler (output range roughly 150 to 220 GHz) was needed which involved a receiver calibration to establish absolute power, input drive leveled to the appropriate point and receiver linearity. The measurement, shown in Figure 8, was compared against spot measurements using a harmonic mixer assembly plus spectrum analyzer which took much longer to complete. Also the harmonic mixer in this case had a 0.1 dB compression point below 0 dBm so additional attenuation was needed for that measurement to be successful. The agreement is within the joint uncertainty bounds of 1.5 dB.

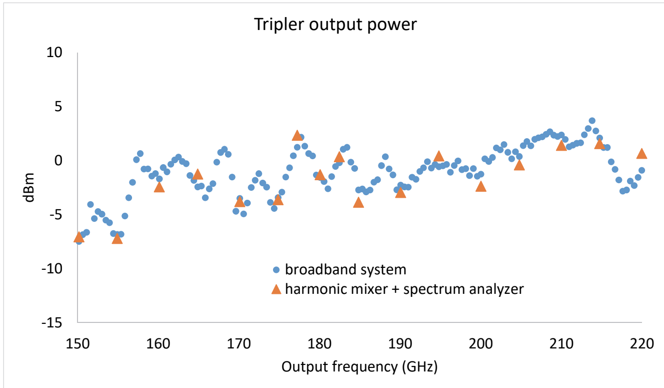

Figure 8 Multiplier output as measured with the current system (with higher point count and absolute receiver calibrations) and with a harmonic mixer/spectrum analyzer pair with padding and additional calibrations showed decent agreement.

5 Conclusions

A broadband 70 kHz to 220 GHz VNA system has been presented that was designed for device/subsystem modeling and characterization. A number of the important design goals and concepts have been discussed including high receiver linearity, wide power control, good measurement stability and functionality to support diverse measurement needs.

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