White Paper

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New VNA Technologies Enable Millimeter-Wave Broadband Testing to 220 GHz

Abstract

Over the past few years there has been growing interest in developing solutions that harness millimeter-wave (mmWave) frequencies for terrestrial communication, high-frequency device characterization, automotive radar, and other technologies. As these applications climb from tens of gigahertz to over 100 gigahertz, the challenge of testing and characterizing the devices that enable new solutions is becoming increasingly complex. As broadband testing over hundreds of gigahertz of bandwidth is subject to repeatability and accuracy deficits, researchers and engineers are demanding better broadband solutions that help to overcome these challenges and simplify mmWave testing.

Introduction

The demand for faster wired and wireless communication speeds, higher resolution automotive radar, and much greater bandwidth for networking infrastructure is driving trends toward much higher data rates and higher frequency wireless communications. As these operating frequencies and data rates increase to hundreds of gigabits-per-second and tens to hundreds of gigahertz, the devices generating, processing, transferring, and receiving these signals are shrinking in size to the point where even complete wireless systems are being built on a single IC. Moreover, the complexity of these ICs is increasing as system-in-package (SiP), system-on-chip (SoC), and three-dimensional integrated circuit (3D IC) technology is being developed to accommodate the higher data rates, transfer speeds, memory, and processing power required to meet the performance demands of these latest applications [1,2,3].

All of these factors contribute to a greater challenge when either characterization, qualification, or inspection testing these new devices that often exhibit broadband frequency response of tens, if not hundreds of gigahertz. To effectively test and characterize these new era mmWave devices, broadband and vector testing equipment is needed that can achieve extreme precision and repeatability. Realizing this is an ever-growing challenge for compact footprint IC/wafer testing.

Millimeter-Wave and Terahertz Potential Current and Future Applications [4]

Category	Application
Communications	High-Speed Mobile Wireless Wireless Backhaul Device-to-Device Communications Data Center Connectivity Satellite-to-Satellite Communications
Sensing	Personal Health Monitoring Gesture Detection Air Quality Explosives and Gas Sensing
Imaging	Darkvision Systems Security Body Scanning Product Quality Control
Wireless Cognition	Autonomous Vehicles Drone Fleet Control Robotic Facility Control
Position	Centimeter-Level Positioning
Radar	High-Resolution Imaging Radar

Trends Raising the Frequency Bar

There are several key application areas that are pioneering the use of mmWave communications and imaging technology. As these applications emerge, there are predictions that these relatively low-volume and high-cost markets will need to transform to high-volume and medium-cost to meet growing demand [1, 2, 3, 4, 5, 6, 7]. These trends include:

- Tactical communications (including terrestrial, aerospace, and satellite)
- 5G communications (including mmWave backhaul at E-band and D-band)
- Unmanned aerial vehicle (UAV) imaging and communications
- Automotive radar
- On-chip radios
- Satcom and new space initiatives

Moreover, there are several other trends that are encouraging military, aerospace, government, public safety, and satellite applications to move from RF and microwave frequencies to mmWave frequencies. As the sub-6 GHz spectrum continues to become cluttered with cellular communications, WiFi, and other mass user applications, these frequencies become less reliable for critical applications. Moreover, new communications applications, such as 5G NR mmWave bands, in the tens of gigahertz are creating communication technology opportunities in these frequency bands as well as incentives for critical communications and radar to move to even higher frequencies.

Millimeter-Wave Test Challenges

With each of these applications, highly integrated digital and mmWave technologies are considered enabling factors. Hence the characterization, prototype, and production testing of amplifiers, mixers, isolators/circulators, filters, attenuators, transmission lines (interconnect), transformers, and other key mmWave components are necessary to refine the design and manufacturing process, pass certification testing, and ensure production quality. For certification, qualification, and production testing, the bulk of these tests are performed at targeted frequency ranges, and can often be simplified in order to meet desired testing speed and quality considerations.

This is not the case with characterization testing, which must be conducted in such a way to ensure the highest accuracy over a frequency range below and above the frequency range and bandwidth of the device under test (DUT). Characterization testing is a necessary part of developing a semiconductor fabrication process, as well as during the design and prototyping stages of electronics. Characterization testing is ultimately used to determine device performance parameters and create device models for electronic computer-aided design (ECAD) systems, which all electronics designers rely on during the development process. How well the characterization testing is performed can often influence how many refining iterations are needed during development, and hence, the length of the development cycle and time-to-market.

The quality of a device model is dictated by the accuracy of the testing as well as the frequency range over which the device is tested. As these recent mmWave applications have devices operating from tens of gigahertz to over 100 gigahertz, this means that during characterization testing equipment that is accurate and calibrated to hundreds of gigahertz is necessary to properly characterize these devices. There are several device phenomena that require characterization testing beyond merely the bandwidth of operation, and if broadband characterization testing isn't performed the models produced are much less accurate. These phenomena include harmonics with nonlinear devices, stability criteria, and higher order modes.

Until recently, there have been two main methods of performing broadband testing for wafer and semiconductor die probing – the concatenated waveguide band approach, and translating optical frequencies and measurement techniques to mmWave spectrum. The reason for this is that current coaxial connectors and cabling are generally only available with operating frequencies to 110 GHz. More recently, 0.8 mm coaxial connectors have become available that operate to 145 GHz [8]. Using this new cabling, along with test instruments that have comparable frequency range, true broadband testing to 145 GHz is now possible.

However, testing beyond this frequency range requires additional hardware and isn't broadband. It is important to note that another justification for using waveguide interconnect for precision testing is that waveguide interconnect typically exhibits much less loss than coaxial interconnect. Since resistive and dielectric losses in a transmission line are a function of frequency, this becomes a greater concern at mmWave frequencies. Hence, the precision manufacturing, quality design, and proper installation are critical in achieving minimal attenuation when deploying mmWave test setups using coaxial interconnect.

Table 1: Millimeter-Wave Coaxial Connector Parameters

Connector Type	Maximum Rated Frequency (GHz)	Air Cutoff Frequency	Center Conductor Diameter (mm)
N-type	18	19.4	3.04
SMA	26	30	1.27
3.5 mm	33	38.8	1.52
2.92 mm	40	46	1.27
2.4 mm	50	56	1.042
1.85 mm	70	73	0.803
1 mm	110	136*	0.434
0.8 mm	145	170*	0.347
0.6 mm	220	226*	0.26
0.4 mm	TBD	339*	0.174

**As the typical equation used for estimating coaxial cutoff frequency is an approximation and the errors of this approximation increases as a function of frequency, the values for air cutoff in this table are derived from a full solution of the transcendental mode equation.*

The concatenated waveguide band approach requires the use of test instruments with frequency extending hardware that uses waveguide interconnects. As waveguides are intrinsically banded interconnect, several frequency extender units, and possibly several test instruments, are required to perform testing to hundreds of gigahertz [9, 10]. For instance, to perform a device characterization test from DC to 220 GHz, a user would have to use a coaxial test interconnect to the probe until they reached the limit of their testing device and/or interconnect. Then the user would need to use a series of frequency extenders that, when merged, reaches the maximum frequency. One method of doing this would be to use a vector network analyzer (VNA) that operates to 110 GHz with a 1 mm coaxial interconnect, then use a frequency extender with D-band waveguide, and follow those tests by another frequency extender using WR5 (140 GHz to 220 GHz) waveguide.

Table 2: Waveguide Band Names, Designations, and Electrical/Mechanical Parameters								
Waveguide Band Names (EIA, RCSC, and IEC)			**Waveguide Frequency Designations**	**Lower Frequency (GHz)**	**Upper Frequency (GHz)**	**Cutoff Frequency**	**Width in. [mm]**	**Height in. [mm]**
WR137	WG14	R70	C band	5.85	8.2	4.301 GHz	1.372 [34.8488]	0.622 [15.7988]
WR112	WG15	R84	H band	7.05	10	5.26 GHz	1.122 [28.4988]	0.497 [12.6238]
WR102				7	11	5.786 GHz	1.02 [25.908]	0.51 [12.954]
WR90	WG16	R100	X band	8.2	12.4	6.557 GHz	0.9 [22.86]	0.4 [10.16]
WR75	WG17	R120		10	15	7.869 GHz	0.75 [19.05]	0.375 [9.525]
WR62	WG18	R140	Ku band	12.4	18	9.488 GHz	0.622 [15.7988]	0.311 [7.8994]
WR51	WG19	R180		15	22	11.572 GHz	0.51 [12.954]	0.255 [6.477]
WR42	WG20	R220	K band	18	26.5	14.051 GHz	0.42 [10.668]	0.17 [4.318]
WR34	WG21	R260		22	33	17.357 GHz	0.34 [8.636]	0.17 [4.318]
WR28	WG22	R320	Ka band	26.5	40	21.077 GHz	0.28 [7.112]	0.14 [3.556]
WR22	WG23	R400	Q band	33	50	26.346 GHz	0.224 [5.6896]	0.112 [2.8448]
WR19	WG24	R500	U band	40	60	31.391 GHz	0.188 [4.7752]	0.094 [2.3876]
WR15	WG25	R620	V band	50	75	39.875 GHz	0.148 [3.7592]	0.074 [1.8796]
WR12	WG26	R740	E band	60	90	48.373 GHz	0.122 [3.0988]	0.061 [1.5494]
WR10	WG27	R900	W band	75	110	59.015 GHz	0.1 [2.54]	0.05 [1.27]
WR8	WG28	R1200	F band	90	140	73.768 GHz	0.08 [2.032]	0.04 [1.016]
WR6	WG29	R1400	D band	110	170	90.791 GHz	0.065 [1.651]	0.0325 [0.8255]
WR5	WG30	R1800		140	220	115.714 GHz	0.051 [1.2954]	0.0255 [0.6477]

This creates several challenges when de-embedding probes, adapters, waveguide runs, and cable assemblies, and ultimately leads to less accurate data that must be combined in ways that lead to degraded device models. Moreover, for each waveguide frequency band used, the test setup must be reconfigured from the prior test, including repositioning the probe on the wafer. As in many circumstances, the DUT may be connected to the landing pads through several vias and metal layers, de-embedding the interconnect from the pads to the DUT already introduces some level of uncertainty to the data [11, 12].

Calibration must also be performed for each setup, however due to the wear on the landing pads, calibration structures, and probes, repeatability of each test is further diminished and the uncertainty of the tests increase. For example, the aluminum pads commonly used with silicon (Si) processes are generally deformed with each probe interaction. As is often the case, different calibration standards may be used, increasing the challenge of successfully de-embedding the test setup. Conversely, with a true broadband measurement system (DC to the max frequency), a very accurate and consistent de-embedding can be performed down to the device level and with fewer touchdowns.

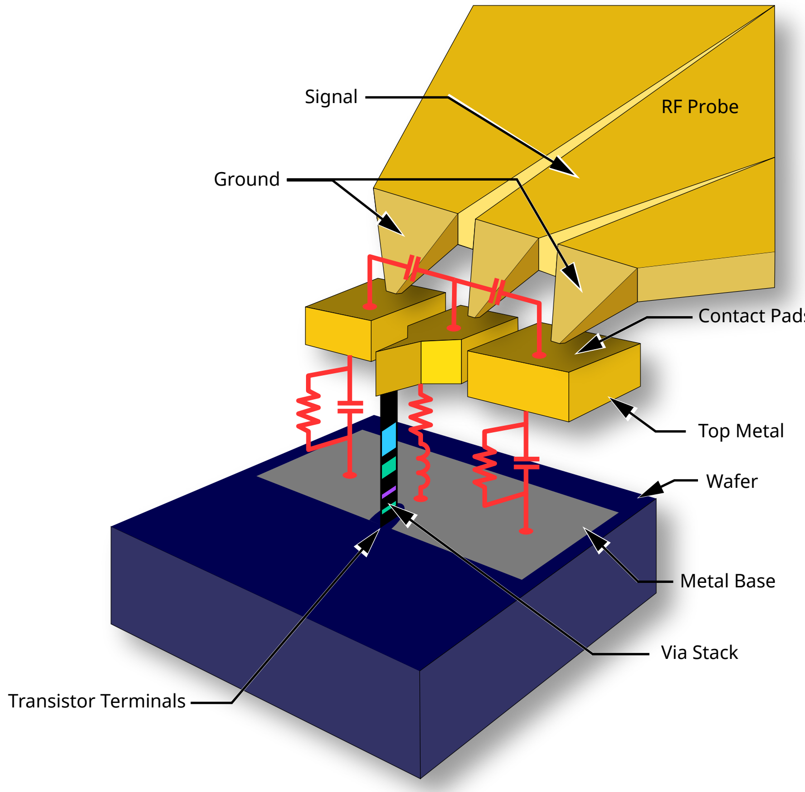

Figure 1. The back-end-of-line (BEOL) parasitic circuit elements and probe interconnect resistances and capacitances increase the uncertainty of on-wafer measurements and impact device model accuracy.

Optical generation and sensing techniques are other possibilities for broadband measurements. Signal generation may be accomplished by mixing optical signals of slightly different wavelengths at the DUT input (with the help of a photodetector either mounted on-wafer or on a probe). The noise level of such mmWave signals may be high and the frequency stability is often a challenge to maintain. Detection can be done conventionally or with optical reconversion, but the latter often compromises the dynamic range of the measurement.

Enabling True Broadband Millimeter-Wave Testing to 220 GHz

There have been recent advances in both test instrument technology and coaxial interconnect that enable true broadband and single-sweep testing from DC to 220 GHz – non-linear transmission line (NLTL) sampling VNA technology and the 0.6 mm coaxial interface. The Anritsu NLTL technology enables high-performance and frequency-scalable VNA architectures that improve over the limitations of step-recovery diode (SRD) VNA systems and those of VNA systems based on some other downconversion technologies. The 0.6 mm coaxial connector system provides DC to 220 GHz of bandwidth while minimizing the issues associated with high loss, repeatability, and mechanical installation of these extremely small interfaces.

Non-Linear Transmission Line (NLTL) Instrumentation

NLTL technology has long been used for pulse shaping and digitizing oscilloscope applications, and has more recently been leveraged by Anritsu to develop a line of compact, high-performance, and frequency-scalable VNAs [13]. NLTL technology differs significantly from SRD-based VNA and other VNA technologies in the way the pulses are generated and the components required to enhance isolation and other performance criteria.

The main limiting factors of SRD-based structures (the step recovery diode does the LO waveform manipulation in those systems) are instability and that they only can support relatively low LO frequencies, leading to degraded noise performance and additional image responses. Because SRDs are quasi-chaotic devices, generally one must be used for LO waveform shaping for all receiver channels which means there will usually be limited isolation between those receivers.

A more modern mmWave VNA structure may use a more classic harmonic mixing structure where the LO port is driven with a sinusoid at some sub-multiple of the final LO frequency and the mixing element itself is used to generate this harmonic. While this is successful, the conversion efficiency and linearity degrade with each increase in that internal multiple (as opposed to staying roughly constant with the NLTL shaped-waveform structure). Thus, as the harmonic order increases, the performance divergence will increase as well (holding device technologies constant). Depending on the devices involved and the relative harmonic generation capabilities, multiple mixers may be needed to cover the wide bandwidths being discussed here.

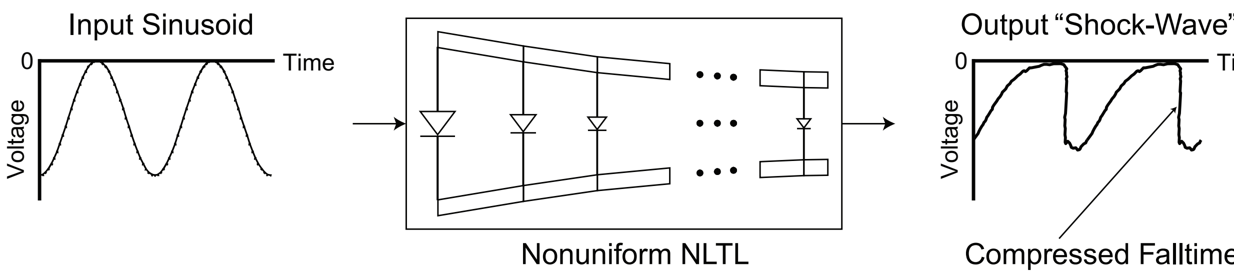

Figure 2. The enhanced fall time compression and use of a differentiator circuit (step differentiation) transforms a continuous wave signal into a train of pulses used for sampler gating.

Anritsu’s NLTL-based VNAs overcome many of these challenges with an innovative architecture as well as the use of monolithic reflectometer designs and components that enhance signal quality, reduce cost, enable extreme bandwidth, mitigate isolation calibration issues, and enable more compact VNAs that can be placed closer to DUTs. NLTL-based VNAs can be made to provide these benefits by using monolithic samplers, directional bridges, multiplexers, and other key components along with distributed harmonic generators. NLTL-based VNA architectures rely on continuous wave signals that then undergo fall-time compression via non-uniform NLTLs to create narrow gating pulses for sampling receivers, and distributed harmonic generation is enabled by using the “harmonic growth” characteristics of NLTLs.

The result is extremely high RF sampler bandwidth with a single sampler covering a much broader range of frequencies with lower noise floor than an SRD-based sampler or many classical harmonic mixers. The use of a high LO range also minimizes noise introduction and image response issues. Moreover, the Anritsu implementation of the NLTL technology results in a coupling structure with positive raw directivity. This raw directivity helps with the modeling process by improving measurement stability and lengthening the amount of time between calibrations. Some other broadband VNA technologies exhibit negative raw directivity, which means that these architectures are much more susceptible to environmental effects reducing calibration integrity and measurement stability.

Hence, NLTL technology benefits from RF and LO frequency scalability and high channel-to-channel isolation without suffering the same degradation from poor isolation that other VNAs experience. Additionally, the monolithic design and compact nature of NLTL-based VNAs reduces the temperature variations between the reflectometers and constituent components, which enhances calibration integrity, measurement accuracy, and measurement repeatability. Lastly, the small size and minimal internal interconnect enables the actual sampling hardware to be placed very close to the DUT, an extremely beneficial feature with millimeter-wave testing to reduce potential attenuation from relatively long and lossy transmission lines.

0.6 mm Interface

The other key element in developing a DC-to-220 GHz and single-sweep test setup is using a non-banded transmission line to enable true broadband testing. However, there are many mechanical hurdles to overcome with designing and manufacturing a sub-millimeter coaxial interface. One of these challenges is ensuring repeatability and reliability with a threaded coaxial connector. With a 0.6 mm coaxial connector interface, the threading on such a connector would require tolerances around 100th of a millimeter in order to properly align the male and female pins. Thread pitch and torque requirements are also critical to maintain concentricity. Given the thread pitch, torque, and tolerance requirements, typical threaded connector wear will substantially reduce the lifetime expectancy of a threaded 0.6 mm coaxial connector.

Anritsu’s solution is to use a tried-and-true method of ensuring good alignment and connection for small mmWave interfaces, a modified male/female pin connector that uses a waveguide flange style (UG-387) interface for alignment. Much like with a typical UG-387 waveguide connection, the new 0.6 mm connectors from Anritsu use precision guide pins to create an extremely reliable, repeatable, and low-loss mating that is also more shock and vibration tolerant than a threaded coaxial connector would be at these dimensions.

This innovation came from the extreme tolerances needed to align the center pins of a 0.6 mm coaxial connector. Moreover, as this type of testing is generally wafer or die probe testing, the precision waveguide flange style mating interface provides higher performance and more reliability than a comparable threaded coax, leading to improved practical accuracy at the calibration plane on the wafer/die surface. Cumulatively, this connecting structure has shown excellent durability over 1000 connection cycles, return loss greater than 20 dB to 220 GHz, and repeatability better than 40 dB at 220 GHz.

Conclusion

This white paper discusses the market and technology trends that are driving demand for higher frequency solutions. Moreover, it provides details of the challenges faced by design engineers as they attempt to perform wafer-level testing over broadband millimeter-wave frequencies. Lastly, illumination is provided on how Anritsu engineers were able to innovate with broadband vector network analyzer (VNA) and mmWave connector technology to enable broadband testing to 220 GHz with a single test unit and setup.

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