Sunday, January 22nd

NIST-ARFTG Short Course on Microwave Measurements

Microwave Fundamentals and Traceable Measurements

08:00 am
—
12:00 pm

SC-1

Microwave Power and Traceability

Aaron Hagerstrom (NIST)

This talk will cover traceable microwave power measurements at NIST. We will describe the dc substitution approach to traceable power measurements and discuss two methods to calibrate power sensors. The first approach is calorimetry, which achieves relatively low uncertainty, but can only be used with specific sensors. The second approach is direct comparison, which is relatively easy and can be used on a much wider variety of power sensors but requires a well-characterized calibration standard.

SC-2

Updating NIST's Traceability: S-Parameters and Beyond

Angela Stelson (NIST)

Traceability of S-parameters to fundamental SI quantities (the second and the meter) is key to assessing uncertainties of microwave measurements across the telecommunications industry. S-parameters are a fundamental microwave-frequency measurand and are part of the traceability chain for numerous quantities, including antenna factors, microwave power, and phase. Here, we outline a comprehensive uncertainty budget for S-parameters in the WR-15 waveguide band with the goal of establishing traceability for these S-parameters, wave parameters, and further derived measurements. The uncertainty analysis presented here begins by evaluating uncertainties related to the imperfect physical dimensions of the calibration standards and test ports. Then, we outline experiments to evaluate instrumentation uncertainties including drift, noise and receiver nonlinearity, and assess their contributions to the total uncertainty of the measurement. Overall, this talk aims to demonstrate a workflow to incorporate the major sources of systematic and statistical uncertainties in S-Parameter measurements to the measurement of unknown devices.

SC-3

Modern Network Analyzers Calibration Techniques

Rusty Myers (Keysight Technologies)

Calibration is crucial for making accurate measurements with a Vector Network Analyzer. This talk will start with basic explanation of VNA calibration to provide the background for historical 1-port and 2-port calibration methods. Next up, modern advances in calibration methods will be explained. It will wrap up with some real world measurement challenges and how these modern techniques can tackle them.

SC-4

High-Speed Oscilloscopes, What the Manual Does't Tell You

Paul D. Hale (NIST)

The differences between high-speed real-time and equivalent-time oscilloscopes will be discussed along with digitizing receivers and the errors inherent in these instruments. Methods for traceably calibrating the instruments with particular emphasis on equivalent-time oscilloscopes will be presented. Some examples of digital and RF measurement configurations will be described with particular attention to achieving the highest possible accuracy and precision.

On-Wafer Measurements

02:00 pm
—
05:00 pm

SC-5

Device Level Calibration and De-embedding Strategies for (sub)mm-wave Devices Technologies

Marco Spirito (Delf University of Technology)

With the reduction of the minimum feature size of ultra-scaled CMOS and HBTs node and their increase in maximum oscillating frequency, the challenge for characterization and modelling engineers lies in performing accurate device level measurements up to sub-mm-wave bands. Conventional approaches based on off-wafer first tier calibrations (ISS) complemented with a lumped based de-embedding approach to remove the test fixture parasitic, provide major limitations when aiming to accurately extract device model up to these frequencies. In this presentation the concept of device level direct calibration/de-embedding will be introduced and the design of Silicon compatible test fixtures to support this approach will be reviewed. Finally, the impact of calibration residual errors on device parameter extraction will be addressed.

SC-6

Fundamentals of Successful On-Wafer-Level System Calibration at mm-Wave Frequencies

Andrej Rumiantsev (MPI Corporation)

The accuracy of the wafer-level calibration procedure can be hindered by several effects, such as unoptimized boundary conditions of calibration standards, unwanted modes propagating in the substrate, the parasitic coupling of calibration standards and RF probe with neighbor elements, specifics of the calibration algorithm used, the impact of the system operator and the laboratory environment, and others. In this discussion, we will review concepts and essential differences in widely used RF calibration methods and their sensitivity to various parasitic effects. We will also address aspects related to the instrumentation and system accessories. Finally, we will review and discuss several examples of improving the confidence of measured data at the mm-wave frequency range.

Over-The–Air (OTA) Measurements (Part 1)

SC-7

Over-the-Air Testing of Wireless Devices

Robert D. Horasky (NIST)

The use of over-the-air (OTA) test is a necessity for characterizing mobile microwave and millimeter-wave wireless devices with antennas that are integrated into transmitters and receivers. Methods for characterizing these devices are discussed, including anechoic chambers, reverberation chambers, and hybrid systems. We will also discuss measurement uncertainty for power-based and vector-based metrics such as total radiated power, receiver sensitivity, and error vector magnitude. These metrics are widely used for assessing both communications and internet-of-things devices in advanced communication systems.

Nonliner Measurements (Part 1)

SC-11

Time-Domain Low-Frequency Active Harmonic Load-pull As a Tool for Verifying the Theory of PA Modes of Operation

J. Apolinar Reynoso-Hernandez (CICESE)

The current and voltage waveforms at the intrinsic current source plane are required to study the behavior of any power amplifier. These waveforms can be obtained either from simulation using nonlinear models along with nonlinear CAD simulators or from measurements. In this Short course, the use of a time-domain LF active harmonic load-pull system is proposed and explained in detail for measuring the current and voltage waveforms at the intrinsic current source plane of GaN-HEMT packaged (on wafer) transistor operated as a R-R class-J mode. From the current and voltage waveforms, the device's drain efficiency and output power, loading the transistor with fundamental and harmonic impedances corresponding to design space of R-R class-J modes, are calculated and compared with those predicted by the theory. This short course demonstrates that R-R class-J modes can be experimentally studied by using time-domain low-frequency active load-pull measurements.

Monday, January 23rd

NIST-ARFTG Short Course on Microwave Measurements

Over-The –Air (OTA) Measurements (Part 2)

08:00 am
—
12:00 pm

SC-8

Millimeter-Wave Measurements in 5G and soon 6G: OTA Becomes Mainstream

Roger Nichols (Keysight Technologies)

Prior to 5G, over-the-air (OTA) measurements of radio systems were the domain of perhaps less than a thousand antenna and OTA-range experts around the world. While all of us electrical engineers are required to take electromagnetic fields classes in our undergraduate years, many of us put those fundamentals behind us are not confronted by the practicalities of measuring fields in the real world. For the most part our concern about fields is constrained to various transmission lines, wafer-probes, and microscopic implementations on integrated circuits. Connecting measurement systems to devices-under-test (DUT's) is simplified through the convenient use of cables and adaptors; and calibration planes are extended to DUT's with easy-to-use software and calibration kits. The advent of millimeter-wave (mmWave) technologies in mainstream commercial communications has driven two significant changes in our measurement industry: 1) these shorter wavelengths eliminate the convenience of DUT-connection through predictable and inexpensive transmission lines; and 2) the number of engineers, physicists, and technicians in the world making the resulting OTA measurements has increased by a factor of somewhere between 10 and 50. This is an talk on an introductory level that will examine the practical fundamentals of connecting to and measuring 5G mmWave DUT's, calibration requirements, and the complexities of directional measurements. It will also include a brief summary of measurements required during design and how these compare and contrast with measurements required by conformance (standards) and compliance (regulatory). I will examine some of the additional complexities driven now by 6G research at frequencies now up to 330GHz. Lastly, I will call out a few intriguing examples of "lessons learned" in the work we have done in this space.

Nonliner Measurements (Part 2)

SC-9

Measuring Modulation Distortion of Devices Using a Vector Network Analyzer

Jan Verspecht (Keysight)

A new method is described to characterize signal distortion of active devices like amplifiers, mixers and frequency converters under modulated operating conditions. The method is called "Modulation Distortion Analysis" and uses a vector signal generator and a vector network analyzer. Modulation distortion analysis is based on the decomposition of the output signal into one part that is linearly correlated with the input signal, and another part that is the nonlinear distortion. The decomposition is based on calculating the statistical cross-correlation between the measured spectra of the input and the output signal. The input signals are repetitive and can be designed to match the statistical and spectral characteristics of any given modulation format. The method has unprecedented dynamic range and accuracy and provides derived quantities like error-vector-magnitude (EVM), noise-power-ratio (NPR), equalized channel capacity, adjacent-channel-power-ratio (ACPR), equalization filter response and best linear approximation filter response.

SC-10

Load Pull Techniques: From the Beginning to Modern Solution

Andrea Ferrero (Keysight)

The load pull techniques have proved extremely successful for both device and system nonlinear measurement and model validation. The course will explore the evolution of such measurement technique from the original mechanical tuner-based system to the more modern electronic load and real time capability. Since the load pull is generally used with highly mismatch devices, particular attention will be also given to calibration and accuracy related argument like: Fixturing, uncertainty on power and on wafer load pull.

SC-12

Everything You Can Do With Vector Nonlinear Microwave Measurements

Patrick Roblin (The Ohio State University)

The advent of nonlinear vector network analyzers (NVNA) has stimulated the introduction of new paradigms in microwave engineering for (1) the measurement, (2) the modeling and (3) the design of nonlinear microwave circuits such as microwave power amplifiers and oscillators. First the various types of NVNA architecture available, the procedure used to calibrate them, and the calibration traceability will be presented. Then the various behavioral models used for the data representation will be reviewed. Circuit-based nonlinear microwave models of transistors can also be directly extracted from large-signal measurements. NVNA’s can further be used to verify the nonlinear embedding device model which predicts from the desired internal PA mode of operation, the required amplitude and phase of the multi-harmonic incident waves at the transistor measurement reference planes. Example of design of power amplifiers (PA) such as Doherty and Chireix amplifiers will be presented.

Speakers Biographies

SC-1

Aaron Hagerstrom (NIST)

Aaron Hagerstrom received the B.S. degree in Physics from Colorado State University in 2010, and the Ph.D. in Physics from the University of Maryland in 2015. He joined National Institute of Standards and Technology (NIST) in 2016 as an NRC postdoctoral associate and developed techniques for microwave-frequency characterization of nonlinear materials and devices. In 2019, he was hired into a staff position at NIST to research traceable power measurements at microwave and mm-wave frequencies.

SC-2

Angela C. Stelson (NIST)

Angela C. Stelson received her B.S. in physics, mathematics, and political science from the University of Oregon in Eugene, OR, USA (2012), and her Ph.D. in Materials Science and Engineering from Cornell University in Ithaca, NY, USA (2017). Her graduate work focused on the electric field-directed assembly of colloids for photonic crystals. She joined the National Institute of Standards and Technology as a National Research Council Fellow in 2017. Currently, she works in the RF Electronics group developing traceable scattering parameter calibrations and new microwave microfluidics measurement techniques for chemical and biological applications.

SC-3

Rusty Myers (Keysight)

Rusty Myers is a Master Metrology Engineer at Keysight Technologies where he is involved in various projects related to measurement science and uncertainties of precision instruments. Most of his work is centered on Vector Network Analyzers and accessories including calibration kits, verification kits, ECal and network analyzer measurement accuracy.

Rusty has extensive experience with passive microwave components and electromechanical devices ranging from RF to sub-mm. During more than a decade at Maury Microwave, Rusty was involved in simulation, design, manufacturing, and test of Maury's complete product portfolio. Over that time, he served in the role of Senior Engineer, Engineering Manager and Director of Engineering. He previously had positions in R&D and manufacturing at Agilent/HP working with a wide range of microwave products. He has a BS in Electrical Engineering with microwave specialization from the University of Illinois, Urbana.

Rusty is an executive committee member for the Automatic Radio Frequency Techniques Group (ARFTG) and has been involved with various aspects for ARFTG conferences. He is an IEEE MTT-S member and has given calibration talks at his local IEEE chapter with plant tours for local students. He is an active participant in the P287 working group for coaxial connectors and previously contributed to the P1785 working group for waveguide standards above 110 GHz.

SC-4

Paul Hale (NIST)

Dr. Paul Hale is Chief of the RF Technology Division in NIST's Communications Technology Laboratory. During Dr. Hale's career at NIST, his work has focused on providing traceability to the International System of Units (SI) for the microwave, high-speed electronics, and optoelectronics industries, including the development of seven measurement services. As part of those efforts, Dr. Hale was a co-developer of the 'full waveform metrology' concept for high-speed electrical waveform measurements at NIST. Under this paradigm the full waveform and its functional representation is the target measurand from which traditional parametric descriptions can be derived. Furthermore, temporal waveforms and their frequency- domain representations are given consistent and equal consideration, with traceability to the

SI, and the ability to transform nominal values and their uncertainties from one domain to the other, simultaneously capturing both in the description. Dr. Hale's recent work has focused on traceable physical measurements for 5G supply chain security and coordinating the NIST metrology R&D effort in response to the CHIPS Act. He was the technical lead on the National Advanced Spectrum and Communication Test Network (NASCTN) test plan development for measuring the user equipment (UE) aggregate long term evolution (LTE) emissions in the AWS-3 Band in 2017 and technical co-lead on the NASCTN 3.5 GHz radar waveform measurements in 2016. Dr. Hale is a Fellow of the IEEE, an Ex Officio member of the International Electronics Manufacturing Initiative (iNEMI) and was an Associate Editor of Optoelectronics/ Integrated optics for the IEEE Journal of Lightwave Technology from June 2001 until March 2007. He has authored or coauthored over 110 technical publications (i10-index=69, Google Scholar, Aug. 4, 2022) and received the NIST Bronze and Silver Awards, U.S. Department of Commerce Gold Award, the Allen V. Astin Measurement Science Award, two ARFTG Best Paper Awards, an ARFTG Best Poster Award, and the NIST Electrical Engineering Laboratory's Outstanding Paper Award. Paul Hale received a Bachelor of Science degree in Engineering Physics and Doctor of Philosophy degree in Applied Physics, both from the Colorado School of Mines, Golden, CO.

SC-5

Marco Spirito (Delf University of Technology)

Marco Spirito (S'01-M'08) received the M.Sc. degree (cum laude) in electrical engineering from the University of Naples "Federico II," Naples, Italy, in 2000, and the Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 2006. In April 2008 he joined the Electronics Research Laboratory at the Delft University of Technology where he is an Associate Professor since April 2013. In 2010 and 2017 he was one of the co-founders of Anteverta-MW and Vertigo Technologies, respectively, two companies pioneering innovative measurement techniques and instruments. His research interests include the development of advanced passive components and building blocks operating in the millimeter and sub-millimeter frequency ranges and the development of characterization setups and calibration techniques for millimeter and sub-millimeter waves.

Dr. Spirito was the recipient of the Best Student Paper Award for his contribution to the 2002 IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM) he received the IEEE MTT Society Microwave Prize in 2008, was a co-recipient of the best student paper award at IEEE RFIC 2011, and the GAAS Association Student Fellowship in 2012 and the Best student paper award at the IMBioC 2018.

SC-6

Andrej Rumiantsev (MPI Corporation)

Andrej Rumiantsev received Diploma-Engineer degree (with highest honors) in Telecommunication systems from the Belarusian State University (BSUIR), Minsk, Belarus, and the Dr.-Ing. Degree (with summa cum laude) in Electrical Engineering from Brandenburg University of Technology (BTU) Cottbus, Germany, in 1994 and 2014, respectively.

He joined SUSS MicroTec Test Systems (from 2010 Cascade Microtech) in 2001, where he held various engineering product management and marketing positions. He significantly contributed to developing the RF wafer probes, wafer-level calibration standards, calibration software, and probe systems. Dr. Rumiantsev is currently with MPI Corporation, holding the position of Director of RF Technologies of the Advanced Semiconductor Test Division. His research interests include RF calibration and wafer-level measurement techniques for advanced semiconductor devices. Dr. Rumiantsev is a member of the IEEE MTT-3 Microwave Measurements Committee, the chair of IEEE MTT-S P2822 Working Group “Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De-Embedding and Measurements" and the ExCom member of the Automatic RF Techniques Group (ARFTG). He holds multiple patents in wafer-level RF calibration and measurement techniques. His doctoral thesis was awarded as “Best Dissertation of 2014 at Brandenburg University of Technologies”.

SC-7

Robert D. Horansky (NIST)

Robert D. Horansky received the B.A. degree in chemistry and the Ph.D. degree in physics from the University of Colorado, Boulder, CO, USA, in 1999 and 2005, respectively. His thesis work focused on low-noise dielectric measurements on novel materials in molecular electronics. Since 2005, he has been with the National Institute of Standards and Technology (NIST), Boulder, CO, USA, where he started out developing the highest resolving power energy dispersive sensor to date. He then went on to develop metrology techniques for single photon sensors in nuclear radiation and optical power measurements. In 2015, he joined the Metrology for Wireless Systems Project in the Communications Technology Laboratory, NIST developing calibrations and traceability for millimeter-wave wireless systems and reverberation-chamber measurements for cellular applications. He is the Secretary of the IEEE P1765 Standards Working Group on Uncertainty for EVM, and the winner of two Department of Commerce Medals for research in LTE Factor Screening and Novel Single Photon Detectors.

SC-8

Roger Nichols (Keysight)

Roger Nichols is an acknowledged subject matter expert in mobile wireless communications design and measurement technologies. He has 37 years of engineering and management experience at Hewlett-Packard, Agilent, and Keysight spanning roles in R&D, marketing, and manufacturing. Having worked on every wireless generation he has been directing Keysight’s 6G program since its inception in 2019. He is a member of the FCC Technological Advisory Council and is also the strategic director of Keysight’s work in wireless standards. Roger holds a BSEE from the University of Colorado, Boulder.

SC-9

Jan Verspecht (Keysight)

Jan Verspecht received the electrical engineering and Ph.D. degrees from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1990 and 1995, respectively. From 1990 until 2002 he was a Research Engineer with the Hewlett-Packard Company and Agilent Technologies. In 2003 he started working as an independent consultant. In 2008 he co-founded the company Verspecht-Teyssier-DeGroote s.a.s. (VTD), where he was responsible for business development. In 2012 VTD was acquired by Agilent Technologies, now Keysight Technologies, where he holds the position of Master Research Engineer.

He is a pioneer of and key contributor to the development of Nonlinear Vector Network Analyzer (NVNA) technology. He invented X-parameters and Modulation Distortion Analysis. He holds 20 patents and he has authored and co-authored the book entitled "X-parameters", over 40 conference papers and 12 refereed journal papers. His research interests include the large-signal characterization and behavioral modeling of RF and microwave components.

Dr. Verspecht is the recipient of the 2002 ARFTG Technology Award and the 2009 Best IMS Oral Presentation Award. In 2007 Dr. Verspecht was elevated to the grade of IEEE Fellow by the IEEE Board of Directors.

SC-10

Andrea Ferrero (Keysight)

Andrea Ferrero, Born in 1962, Full Professor of Microwave Instrumentation at Politecnico di Torino, Italy, until 2012. From 2013 he joined Agilent Technology (now Keysight Technologies) as principal research engineer. Prof. Ferrero has been a member of the IEEE Technical Committee (MTT11) for microwave measurements, an international reviewer for the EC metrology program, Distinguished Microwave Lecture for the IEEE MTT Society and from 2011 he is an IEEE Fellow. He is the recipient of the IEEE ARFTG Technology Award, and he served as reviewer for Italian ministry of education and for several other universities in Italy and abroad. His 35 years research career span from VNA calibration and uncertainty, Load Pull Techniques, Innovative Microwave device and more recently ultra-fast data acquisition and management algorithms. Andrea Ferrero is the author or coauthor of over 100 papers, and he has been Associated Editor for the IEEE MTT Transaction.

SC-11

J.Apolinar Reynoso-Hernández (CICESE)

J.Apolinar Reynoso-Hernández (AM'92-M'2003) received his Electronics and Telecommunications Engineering degree, M. Sc. degree in Solid State Physics and Ph. D. degree in Electronics, from ESIME-IPN, Mexico, CINVESTAV-IPN, Mexico and Université Paul Sabatier-LAAS du CNRS, Toulouse, France, in 1980, 1985 and 1989 respectively. His doctoral thesis was on Low-frequency noise in MESFET and HEMTs. Since 1990 he has been a researcher at the Electronics and Telecommunications Department of CICESE in Ensenada, B. C., Mexico. His areas of specialized research interest include high-frequency on-wafer measurements, high-frequency device modeling, linear and non-linear device modeling. Among the most outstanding contributions of Prof. Reynoso-Hernández and his research group to the theory of VNA calibration techniques are developing the LZZ calibration technique and the generalized theory of the TRM calibration technique. He has contributed more than 15 publications at the ARFTG and has leaded CICESE's, Microwave group to obtain the best interactive forum paper award five times. Since 2013 he has served as TPC of ARFTG and ARFTG-MTT Workshop organizer, ExCom member of the Automatic RF Techniques Group (ARFTG) and Associated Editor for the IEEE MTT Transaction.

SC-12

Patrick Roblin (The Ohio State University)

Patrick Roblin was born in Paris, France, in September 1958. He received the Maitrise de Physics degree from the Louis Pasteur University, Strasbourg, France, in 1980, and the M.S. and D.Sc. degrees in electrical engineering from Washington University, St. Louis, MO, in 1982 and 1984, respectively. In 1984, he joined the Department of Electrical Engineering, at The Ohio State University (OSU), Columbus, OH, as an Assistant Professor and is currently a Professor. His present research interests include the measurement, modeling, design and linearization of non-linear RF devices and circuits such as oscillators, mixers, power-amplifiers and MIMO systems. From 2016 to 2018 he served for three years as Distinguished Microwave Lecturer for IEEE-MTT.