Sunday, January 21st

NIST-ARFTG Short Course on Microwave Measurements

Join us for a practical tutorial on microwave measurements for wireless communications! This short course is intended for engineers, graduate students, experienced technicians, or technical managers, and will be a learning experience for anyone who wants to improve their knowledge of precision microwave measurements.

This year, the presentations are focused on four broad areas: (1) Microwave fundamentals and traceable measurements; (2) On-wafer measurements, (3) Noise: High frequency and Low-frequency measurements and applications (4) Nonlinear Measurements. In addition, we plan to host a live question and answer session with a panel consisting of short course instructors.

Day one, for the morning, we focus on Fundamental topics include (1) Microwave Power and Traceability; (2) Updating NIST's Traceability: S-Parameters and Beyond; (3) Modern Network Analyzer Calibration Techniques; and (4) High-Speed Oscilloscopes, What the Manual Doesn't Tell You.

Day one, for the afternoon, we focus on the on-wafer topics include presentations on (5) Traceable On-Wafer Measurements at mm-Wave Frequencies; (6) Fundamentals of Successful Wafer-Level System Calibration at the mm-Wave Frequencies. The Noise Measurements topics include presentation on (7) Microwave Thermal Noise – Measurements and Applications; (8) Low-Frequency Noise Measurements and Applications.

Day two, for the morning, we focus on the Nonlinear measurements the topics include presentation on (9) Measuring Modulation Distortion of Active devices Using a Vector Network Analyzer; (10) Load-Pull metrology and applications; (11) Time-Domain Low-Frequency Active Harmonic Load-Pull As a Tool for verifying the Power amplifier modes operation; (12) Everything You Can Do with Vector Nonlinear Microwave Measurements.

Scheduled instructors include: Aaron Hagerstrom (NIST), Angela Stelson (NIST), Rusty Myers (Keysight Technologies) , Ari Feldman (NIST), Uwe Arz (Physikalisch-Technische Bundesanstalt), Andrej Rumiantsev (MPI Corporation), Jean Guy Tartarain (LAAS du CNRS), Gu Dazhen (NIST), Jan Verspecht (Keysight Technologies), Mauro Marchetti (Anteverta-mw), J. Apolinar Reynoso-Hernandez (CICESE), and Patrick Roblin (The Ohio State University).

For questions and suggestions, contact: J. Apolinar Reynoso-Hernández, CICESE, Ensenada, B.C, Mex (apolinar@cicese.mx), the NIST-ARFTG Short Course Coordinator

08:00 – 12:00

Measurements Fundamentals

SC-1

Microwave Power and Traceability

Aaron Hagerstrom (NIST)

International trade requires standardization of measurements between countries. In principle, this standardization is achieved through the concept of metrological traceability. Roughly speaking, a traceable measurement of a physical quantity can be compared to the physical constants that define the SI units, such as the speed of light and Planck's constant, through an unbroken chain of measurements with uncertainties. In this talk, we will discuss what traceability means in practical terms, from the perspective of a person who performs measurements. In particular, we will focus on microwave power measurements at NIST. These measurements are traceable to scattering parameters and DC power. We will describe how we achieve traceability for these measurements, and how traceability can be extended to other measurements. This talk will emphasize uncertainty evaluation, as understanding measurement uncertainty is important not just for traceability, but also for measurements in general.

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. He was part of the team who received the 2022 Allen V. Astin Measurement Science Award for the development of a rigorous new traceability path for microwave power and scattering parameter measurements at millimeter-wave frequencies relevant for new 5G/6G wireless communications systems.

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.

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

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.

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

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

Ari D. Feldman (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.

Ari D. Feldman received his B.S. in Engineering Physics in 2006 and Ph.D. in Materials Science in 2012 from the Colorado school of Mines, Golden, CO, USA. His doctoral thesis involved the study of anomalous photoconductive decay measurements in silicon under high-optical-injection conditions. Continuing his research on photodetectors, in 2012 he joined the Sensors and Detectors Group as a post-doctoral researcher at the National Institute of Standards and Technology, Boulder, CO. In the Fall of 2013, he was awarded the National Research Council Post-Doctoral Fellowship and joined the High-Speed Measurements Group to develop high-speed photodetectors. As a staff researcher he has contributed to a variety of projects including the Gold Award winning LTE Impacts on GPS and Terahertz Synthesizer IMS. In 2019, he took on the role of the Group Leader for the High-Speed Waveform Metrology Group. As of the fall of 2023, he is the acting Division Chief for the RF Technology Division at NIST.

13:00 – 14:45

On-Wafer Measurements

SC-5

Traceable On-Wafer Measurements at mm-Wave Frequencies

Uwe Arz (PTB)

Currently, on-wafer traceability is directly linked to Multiline TRL, which is widely recognized as one of the most accurate on-wafer calibrations. In industrial applications, however, fixed-distance calibrations such as SOLT, LRM or SOLR using commercial impedance standard substrates (ISS) are usually preferred for measurements in a great variety of substrate technologies. In this talk, we will show how traceable uncertainties can be obtained for reference multiline TRL calibrations on different substrates. Next, we will demonstrate how these traceable uncertainties can be transferred to industrial calibrations as mentioned above, enabling fixed-distance lumped-element calibrations with commercial ISS, suitable for the targeted application and including uncertainties. Key is the proper characterization of lumped-element standards on the commercial ISS with custom-made, application-specific reference calibration standards.

Uwe Arz (S'97-M'02-SM'09) received the Dipl.-Ing. degree in electrical engineering and the Ph.D. degree (summa cum laude) from the University of Hannover, Hannover, Germany, in 1994 and 2001, respectively. In 2001, he served as a Post-Doctoral Research Associate with the National Institute of Standards and Technology, Boulder, CO, USA. In 2002, he joined the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, where he develops metrology for on-wafer measurements. From 2015 to 2018, he led the European EMPIR Project PlanarCal as a Coordinator. He is currently the Head of the Working Group On-Wafer Scattering Parameter Measurements at PTB. Dr. Arz is the recipient of the first ARFTG Microwave Measurement Student Fellowship Award in 1999 and of the 2003 AHMT Measurement Award presented by the Association of German University Professors for Measurement Science. He received three ARFTG Best Poster and two ARFTG Best Paper Awards, and was a co-recipient of the 2011 European Microwave Prize. He has authored and coauthored more than 100 publications in the fields of on-wafer S-parameter measurements, broadband characterization of high-speed interconnects, high-impedance probing, network analyzer calibration and dielectric material measurements. In January 2023, he was honored as an ARFTG Life Member.

SC-6

Fundamentals of Successful Wafer Level 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 temperature, 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.

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”.

15:00 – 17:00

Noise Measurements

SC-7

Microwave Thermal Noise – Measurements and Applications

Gu Dazhen (NIST)

Thermal noise measurement is among most challenging tasks in microwave metrology. Despite its random nature, thermal electromagnetic noise is a realization of stationary processes governed by Planck’s radiation law. In this short course, we start by introducing the basics of thermal noise and various definitions arising from noise modeling in microwave network analysis. Next, we discuss noise- temperature measurements, including various techniques and instruments. The measurement discussions cover from metrology-grade insustruments, such as radiometers, to off-the-shelf commercial instruments, such as noise-figure meters or analyzers. In addition, we will briefly touch on more challenging topics, such as cryogenic, on-wafer, and over-the-air noise measurements. We conclude the short course by presenting a few applications where noise measurements are critical.

Dazhen Gu received the Ph.D. degree in electrical engineering from University of Massachusetts, Amherst, in 2007. He joined the RF Technology Division, National Institute of Standards and Technology, Boulder, CO, in November 2003. During the first three and a half years, he did his doctoral research in development of terahertz imaging components and systems. From 2007 to 2009, he was with the Microwave Measurement Services project, where he was engaged in microwave metrology, in particular thermal noise measurements and instrumentation. From 2009 to 2015, he took a position in the microwave remote-sensing project and led the development of traceable microwave brightness- temperature standards. From 2015 to 2018, he got involved in the microwave power project and demonstrated the NIST power traceability with correlated uncertainties for 5G communication researches. Since March 2018, he has been with the Shared-Spectrum Metrology Group, where he continues his research work in noise measurements with applications to various fields.

SC-8

Low-Frequency Noise Measurements and Applications

Jean-Guy Tartarain, LAAS du CNRS

This presentation concerns the metrology and applications of low frequency noise in the field of very high frequency electronics. Noise metrology has its own constraints, and its own mathematical relationships to translate the fine mechanisms that define the electronic detection thresholds. The presentation will take place in two parts: one dedicated to the metrology of LF noise (LFN) measurements and the other related to their application. The optimization and definition of an experimental device for the LFN depend on its specifications, which itself depends on the targeted limits to be measured or the ease of use for the targeted buyer. The definition of the measurement setup (and their associated equations), the compromises of settings (gain, bandwidth, RF-DC decoupling and current and impedance levels) are given by the presentation of different setups. A comparison of the advantages, drawbacks and limitations is given between home-made and commercial setups. User-friendly ease of use and detection noise floor are primarily defined by the trade-off between the ability to drive the DC signal generator or to bias the DUT from batteries. Many performances that define the quality of the LFN measurement arise from these RF-DC decoupling considerations. The second part of the presentation focuses on the applications of these LF noise measurements; it distinguishes the design of RF circuits from the study of noise sources and their evolution during the application of stresses (DC, Thermal, RF) for reliability studies.

Jean-Guy Tartarin was born in Toulouse (France) on March 23, 1972. He received the Ph.D. degree in electrical engineering from Paul Sabatier University, Toulouse, France, in 1997. Since 1998, he has been a researcher at the Laboratoire d'Analyse et d'Architecture des Systèmes du Centre National de la Recherche Scientifique (LAAS-CNRS), and an associate Professor of Electrical Engineering at Paul Sabatier University. Since 2010, he is full Professor at University of Toulouse – Paul Sabatier University. His interests are in noise measurement and modelling (non-linear LF noise and linear HF noise parameters) of solid-state microwave transistors (HBT, HEMT) on III-V, SiGe and GaN technologies. He is also involved in the design of MIC and MMIC low noise microwave circuits, such as low noise amplifiers and low phase noise oscillators, and in the study of reliability of microwave devices. Pr. Tartarin is Head of a European Platform for LF noise characterization, in partnership with Keysight. He is the Scientific Coordinator of the "High-Frequency Devices for telecommunications" group of the PROOF platform dedicated to the study of the reliability of wide bandgap active devices. He owns 10 patents and software releases and he is (co)-author of 30 journal articles and of 92 international conferences contributions and invited papers.

Monday, January 22nd

NIST-ARFTG Short Course on Microwave Measurements

08:00 —12:00	**Nonlinear Measurements**

SC-9

Measuring Modulation Distortion of Active 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.

Jan Verspecht received a Ph.D. degree in Applied Sciences from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1995. From 1990 until 2002 he was a Research Engineer with HP and Agilent. In 2003 he started working as an independent consultant. In 2008 he co-founded the startup VTD. In 2012 VTD was acquired by Agilent Technologies, now Keysight Technologies, where he works as an Intrapreneur. He is a pioneer of and key contributor to Nonlinear Vector Network Analyzer (NVNA) technology, he invented X-parameters and Modulation Distortion Analysis. He holds 20 patents, and he 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. In 2007 Dr. Verspecht was elevated to the grade of IEEE Fellow by the IEEE Board of Directors.

SC-10

Load-Pull Metrology and Applications

Mauro Marchetti (Anteverta-mw)

This presentation focuses on load-pull measurement systems and applications. We will discuss the architecture and the design aspects of state-of-the-art load-pull measurement systems. We will discuss how to evaluate and verify measurement accuracy and describe a procedure for evaluating traceable uncertainty of power measurements as a function of the load impedance.

We will present several application examples, ranging from high speed load-pull for technology evaluations and power amplifier design to modulated testing for 5G applications.

Mauro Marchetti received the B.S. and the M.Sc. degree in electrical engineering from the University of Naples “Federico II,” Italy, and the Ph.D. degree from Delft University of Technology, The Netherlands. In 2006 he joined the Electronics Research Laboratory, Delft University of Technology as a Ph.D. researcher. In 2010 he co-founded and was appointed CEO of Anteverta-mw B.V, a company providing pioneering solutions in the fields of load pull device characterization and high performance power amplifier design. In 2015 Anteverta-mw B.V. was acquired by Maury Microwave Corporation. Since 2022 he is Vice President of Engineering at Maury Microwave Corporation.

SC-11

Time-Domaine Low Frequency Active Harmonic Load-pull As a Tool for verifying the theory of PA Modes of Operation

J. Apolinar Reynoso-Hernández (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.

Prof. 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 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 Work shop organizer.

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.

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.