17-22 January 2021
Virtual Conference

2021 IEEE Radio & Wireless Week
96th ARFTG Microwave Measurement Symposium

NIST-ARFTG Short Course on Microwave Measurements

Overview

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 short course will be presented in an entirely virtual platform. Presentations are focused in three broad areas: (1) Microwave fundamentals and traceable measurements; (2) On-wafer and nonlinear measurements; and (3) Over-the-Air (OTA) measurements. In addition, we plan to host a live question and answer session with a panel consisting of short course instructors.

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. The on-wafer and nonlinear measurements area includes presentations on (5) On-Wafer Materials Measurements; (6) Toward Optical-Based Microwave Probe Measurements; (7) Device Level Calibration and De-embedding Strategies for (sub)mm-wave Device Technologies; (8) Basic Principles of Successful On-wafer RF System Calibration; and (9) Everything You Can Do With Vector Nonlinear Microwave Measurements. We are pleased to include for the first time this year a focus area on over-the-air (OTA) measurements, including presentations on (10)
Day 2 (morning only) will focus on computational tools and nonlinear measurements, including (9) applications of the NIST microwave uncertainty framework, (10) Over-the-Air Testing of Wireless Devices; (11) 5G Millimeter Wave OTA Measurements: OTA Becomes Mainstream; and (12) Over the air characterization: is it not just a dimension more?

Scheduled instructors include: Aaron Hagerstrom (NIST), Angela Stelson (NIST), Rusty Myers (Keysight Technologies), Paul Hale (NIST), James Booth (NIST), Nathan Orloff (NIST), Marco Spirito (Delft University of Technology), Andrej Rumiantsev (MPI Corporation), Patrick Roblin (The Ohio State University), Kate Remley (NIST), Roger Nichols (Keysight), and Marc Vanden Bossche (NI).

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Short Course Coordinator

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Agenda

Fundamental Measurements
Microwave Power and Traceability (ARFTG30)
Aaron Hagerstrom, NIST
Updating NIST's Traceability: S-Parameters and Beyond (ARFTG31)
Angela Stelson, NIST
Modern Network Analyzer Calibration Techniques (ARFTG32)
Rusty Myers, Keysight Technologies
High-Speed Oscilloscopes, What the Manual Doesn't Tell You (ARFTG33)
Paul D. Hale, NIST

On-Wafer/NonLinear Measurements
On-Wafer Materials Measurements (ARFTG34)
James C. Booth, NIST
Device Level Calibration and De-embedding Strategies for (sub)mm-wave Device Technologies (ARFTG36)
Marco Spirito, Delft University of Technology
Basic Principles of Successful On-wafer RF System Calibration (ARFTG37)
Andrej Rumiantsev, MPI Corporation
Everything You Can Do With Vector Nonlinear Microwave Measurements (ARFTG38)
Patrick Roblin, The Ohio State University

Over-the-Air Measurements
Over-the-Air Testing of Wireless Devices (ARFTG39)
Kate Remley, NIST
5G Millimeter Wave OTA Measurements: OTA Becomes Mainstream (ARFTG40)
Roger Nichols, Keysight
Over the air characterization: is it not just a dimension more? (ARFTG41)
Marc Vanden Bossche, NI

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Abstracts

Microwave Power and Traceability (ARFTG30)
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.

Updating NIST's Traceability: S-Parameters and Beyond (ARFTG31)
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, assess their contributions to the total uncertainty of the measurement. Overall, this talk aims to demonstrate a workflow to incorporate the major sources of uncertainty in S-Parameter measurements to devices-under-test.

Modern Network Analyzer Calibration Techniques (ARFTG32)
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.

High-Speed Oscilloscopes, What the Manual Doesn't Tell You (ARFTG33)
Paul 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 Materials Measurements (ARFTG34)
James C. Booth – NIST
Electromagnetic material properties are critical to the development of accurate finite-element and circuit models for integrated devices and components at microwave and mm-wave frequencies. We will present measurement and modelling approaches to quantitatively determine fundamental material properties, such as the electrical conductivity, permittivity, and permeability, as a function of frequency of a range of materials, including substrates, thin films, and complex fluids. We discuss ways in which these fundamental material properties can be controlled or modified through the application of external controls, such as bias voltage and temperature, and attempt to relate materials properties to fundamental physical effects at microwave and mm-wave frequencies.

Device Level Calibration and De-embedding Strategies for (sub)mm-wave Device Technologies (ARFTG36)
Marco Spirito – Delft University of Technology
With the constant upscale of maximum oscillation frequency of silicon based technologies the key question on how to extract accurate models to predict the device operation in the (sub)mm-wave range is more actual than ever before.
In this talk we will review the main concepts and differences between de-embedding and direct device level calibration. We will highlight some of the key features to be embedded in the device test fixture to support accurate direct calibration. Finally, we will analyse some results on test fixtures fabricated in state of the art Silicon based technologies for the direct extraction of device parameters to provide precise inputs for model generation.

Basic Principles of Successful On-wafer RF System Calibration (ARFTG37)
Andrej Rumiantsev - MPI Corporation
Accurate isothermal characterization of high-frequency devices at millimetre and sub-millimetre wavelengths demands for on-wafer system calibration. This approach locates the calibration and measurement reference plane close to the device terminals in one step minimising or completely eliminating measurement errors due to temperature difference, contact pads used of off-wafer (alumina substrate) standards and the wafer, as well as the probe-to-pad coupling. In this presentation we will review the basic principles of system calibration with custom-made calibration standards, including but not limited to such aspects as how to choose calibration method, what to consider when designing the calibration standards, and where is the optimal location of the calibration reference plane. Some practical examples will also be given.

Everything You Can Do With Vector Nonlinear Microwave Measurements (ARFTG38)
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.

Over-the-Air Testing of Wireless Devices (ARFTG39)
Kate Remley - 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, with an emphasis on measurement uncertainty for power-based metrics such as total radiated power and receiver sensitivity. These metrics are widely used for assessing both communications and internet-of-things devices in advanced communication systems.

5G Millimeter Wave OTA Measurements: OTA Becomes Mainstream (ARFTG40)
Roger Nichols - Keysight
Prior to 5G, over-the-air (OTA) measurements of radio systems were the domain of maybe a few thousand antenna and OTA-range experts around the world. While all of us electrical engineers are required to take a few electromagnetic fields classes in our undergraduate years, most of us put those fundamentals behind us are not confronted by the realities of measuring antenna systems in the real world. We do spend much of our careers thinking of electromagnetic fields, but for the most part, such thinking is constrained to various transmission lines, wafer-probes, and microscopic implementations in integrated circuits. Connecting measurement systems to devices-under-test (DUT's) gets 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 20 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). Lastly I will call out a few intriguing examples of “lessons learned” in the work we have done in this space.

Over the air characterization: is it not just a dimension more? (ARFTG41)

Marc Vanden Bossche - NI

The short course will take the attendee from the known conductive world traveling into an antenna to leave the antenna and to start travelling into free space going from very close to the antenna to far away from the antenna. Different aspects of the fields will be discussed.

As a next step, antenna characterization techniques are discussed to provide a detailed enough overview of available approaches with their pros and cons. The goal is to enable the listener with the knowledge to evaluate what techniques are best for her or his problem.
Finally, the goal is to discuss the characterization of phased array antennas in general from the design to production phase.

The short course will also discuss the measurement challenges and the uncertainties introduced as antennas are being characterized.

NIST-ARFTG Short Course on Microwave Measurements

Instructor Biographies

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.

Angela C. Stelson received the B.S. degree in physics, mathematics, and political science from the University of Oregon, Eugene, OR, USA, in 2012 and the Ph.D. degree in materials science and engineering from Cornell University, Ithaca, NY, USA, in 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 to work on developing on-chip microwave microfluidic measurements of complex solutions. She currently works in the RF Electronics Group developing new microwave calibrations and measurements in on-chip, waveguide and coaxial devices for applications in telecommunications, bioelectronics and analytical chemistry.

Rusty Myers is a Senior 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 Advanced 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.

Paul Hale received a Bachelor of Science degree in Engineering Physics in 1985 and Doctor of Philosophy degree in Applied Physics in 1989, both from the Colorado School of Mines, Golden, CO. He was with the Optoelectronics Division of the National Institute of Standards and Technology (NIST), Boulder, CO, from 1989 until 2014, where he conducted research on broadband optoelectronic device and signal metrology. From 2015 to 2019 he was Leader of the High-Speed Measurements Group in the RF Technology Division of NIST's newly created Communications Technology Laboratory. Dr. Hale is now Chief of the RF Technology Division. Dr. Hale's research focuses on implementing a covariance-based uncertainty analysis that can be used for mixed-domain quantities of interest for wireless communications, wireless coexistence, and dissemination of NIST traceability for mm-wave applications through high-speed electronic and optoelectronic measurement services. Dr. Hale was technical co-lead on the NASCTN 3.5 GHz radar waveform measurements at Point Loma and Virginia Beach and was technical lead on the NASCTN test plan development for measuring the user equipment (UE) aggregate long term evolution (LTE) emissions in the AWS-3 Band.

Dr. Hale 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 100 technical publications and received the Department of Commerce Bronze, Silver, and Gold Awards, the Allen V. Astin Measurement Science Award, two ARFTG Best Paper Awards, and the NIST Electrical Engineering Laboratory's Outstanding Paper Award. Dr. Hale is a Fellow of the IEEE.

James Booth received the B.A. degree in Physics from the University of Virginia in 1989 and the Ph.D. degree in Physics from the University of Maryland in 1996, where the subject of his dissertation was "Novel measurements of the frequency dependent microwave surface impedance of cuprate thin film superconductors." He has been a physicist at the National Institute of Standards and Technology (NIST) in Boulder, CO since 1996, originally as an NRC postdoctoral research associate (1996-1998) and currently as Leader of the RF Electronics Group within the Communications Technology Laboratory. His research at NIST is focused on quantifying the microwave properties of new electronic materials and devices, including piezoelectric, ferrite, magneto-electric and superconducting materials, as well as linear and nonlinear measurements and modeling of analog components such as transmission lines and filters.

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.

Andrej Rumiantsev received the Diploma-Engineer degree (with highest honors) in Telecommunication systems from the Belarusian State University of Informatics and Radio Electronics (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 January 2010 Cascade Microtech) in 2001 where he held various positions in engineering, product management and product marketing. He significantly contributed to the development of the RF wafer probe, the |Z| Probe, wafer-level calibration standards, calibration software and probe systems. In March 2013, he joined Ulrich L. Rohde Chair for RF and Microwave Techniques at Brandenburg University of Technologies (BTU), Cottbus, Germany. Dr. Rumiantsev is currently with MPI Corporation, holding a 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-11 Microwave Measurements Committee and the ExCom member of Automatic RF Techniques Group (ARFTG). He is the past ExCom member and Chair of the Modeling and Simulation Sub-Committee of IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM/BCICTS), Technical Program Chair of ARFTG-92nd and ARFTG-93rd and the General co-Chair of ARFTG-94th and ARFTG-96th. He holds multiple patents in the area of wafer-level RF calibration and measurements techniques. Dr. Rumiantsev received the ARFTG-71th Best Interactive Forum Paper Award. His doctoral thesis was awarded as "Best Dissertation of 2014 at Brandenburg University of Technologies".

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.

Kate A. Remley (S'92-M'99-SM'06-F'13) was born in Ann Arbor, MI. She received the Ph.D. degree in Electrical and Computer Engineering from Oregon State University, Corvallis, in 1999.

From 1983 to 1992, she was a Broadcast Engineer in Eugene, OR, serving as Chief Engineer of an AM/FM broadcast station from 1989-1991. In 1999, she joined the RF Technology Division of the National Institute of Standards and Technology (NIST), Boulder, CO, as an Electronics Engineer. She is currently the Leader of the Metrology for Wireless Systems Project at NIST, where her research activities include development of calibrated measurements for microwave and millimeter-wave wireless systems and standardized over-the-air test methods for the wireless industry.

Dr. Remley is a Fellow of the IEEE and was the recipient of the Department of Commerce Bronze and Silver Medals, an ARFTG Best Paper Award, the NIST Schlichter Award, and is a member of the Oregon State University Academy of Distinguished Engineers. She was the Chair of the MTT-11 Technical Committee on Microwave Measurements (2008-2010), the Editor-in-Chief of IEEE Microwave Magazine (2009-2011), and Chair of the MTT Fellow Evaluating Committee (2017-2018). She was a Distinguished Lecturer for the IEEE Electromagnetic Compatibility Society (2016-2017).

Roger Nichols’ 36 years of engineering and management experience in wireless test and measurement at Hewlett-Packard, Agilent Technologies, and Keysight spans roles in manufacturing, R&D, and marketing. He has managed programs, projects, and departments starting with analog cellular radio, evolving to 6G, and on every standard in between. He has been directing Keysight’s 5G program since 2014, and Keysight’s 6G program since 2019. He is also the director of Keysight’s work in wireless standards.

Roger holds a BSEE from the University of Colorado, Boulder.

Marc Vanden Bossche received the Ph.D. degree in 1990 from Vrije Universiteit Brussel in electrical engineering focusing on the foundation of high frequency large-signal network analysis. In 1991 he established a Hewlett Packard R&D team in Belgium continuing to work on characterization and system-level modeling tools for high frequency nonlinear electrical components, leading to the expansion of the capabilities of VNA's. In June 2003 Marc founded NMDG, which was acquired by National Instruments in October 2012. Presently he is working on and leading RF calibration and advanced characterization techniques, both conductive and over the air, for design and production test applications using modular instrumentation.
Marc is senior IEEE member. He was a corecipient of the 2002 ARFTG Technology Award and recipient of two ARFTG Best Paper Awards and is author of 7 patents.