94th ARFTG Microwave Measurement Conference

NIST-ARFTG SHORT COURSE
on
Microwave Measurements

January 26th – 27th, 2020

San Antonio, Texas

ARFTG-NIST Short Course on Microwave Measurements

Jan. 26th-27th, 2020
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Overview:

Join us in a tutorial on practical microwave measurements for wireless communications. This short course is intended for engineers, graduate students, experienced technicians, or technical managers.

Day 1 will start in the morning session with fundamental topics, including (1) modern network analyzer calibration techniques, (2) microwave power and traceability, (3) high-speed oscilloscopes, what the manual doesn't tell you, and (4) on-wafer materials measurements. Day 1 continues in the afternoon session with on-wafer measurement topics, including (5) fundamentals of on-wafer measurements, (6) traceable on-wafer measurements at mm-wave frequencies, (7) non-contact on-wafer probing for mm-wave and THz applications, and (8) on-wafer system calibration for mm-wave frequency applications.

Day 2 (morning only) will focus on computational tools and nonlinear measurements, including (9) applications of the NIST microwave uncertainty framework, (10) mult-physics measurements and modeling, (11) everything you can do with vector nonlinear microwave measurements, and conclude with (12) introduction to X-parameters.

Scheduled Instructors:

- Rusty Myers – *Keysight Technologies*
- Aaron Hagerstrom – *NIST*
- Paul Hale – *NIST*
- James Booth - *NIST*
- Dylan Williams – *NIST*
- Uwe Arz - *PTB*
- Kubilay Sertel – *The Ohio State University*
- Marco Spirito – *Delft University of Technology*
- *Andrej Rumiantsev – MPI Corporation*
- Jeffrey Jargon – *NIST*
- Peter Aaen – *Colorado School of Mines*
- Patrick Roblin – *The Ohio State University*
- Jan Verspecht – *Keysight Technologies*

Contact:

James C. Booth, NIST, Boulder, CO, USA (james.booth@nist.gov)
Short Course Coordinator

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AGENDA

Day 1

7:30 a.m. – 8:00 a.m.	**Registration**
8:00 a.m. – 8:10 a.m.	**Welcome and Introduction** *James C. Booth – NIST*
8:10 a.m. – 9:00 a.m.	**Modern Network Analyzer Calibration Techniques** *Rusty Myers – Keysight Technologies*
9:00 a.m. – 9:50 a.m.	**Microwave Power and Traceability** *Aaron Hagerstrom – NIST*
9:50 a.m. – 10:20 a.m.	**Break**
10:20 a.m. – 11:10 a.m.	**High-Speed Oscilloscopes, What the Manual Doesn't Tell You** *Paul D. Hale - NIST*
11:10 a.m. – 12:00 p.m.	**On-Wafer Materials Measurements** *James C. Booth – NIST*
12:00 p.m. – 1:00 p.m.	**Lunch**
1:00 p.m. – 1:50 p.m.	**Fundamentals of On-Wafer Measurements** *Dylan Williams – NIST*
1:50 p.m. – 2:40 p.m.	**Traceable On-Wafer Measurements at mm-Wave Frequencies** *Uwe Arz – PTB*
2:40 p.m. – 3:10 p.m.	**Break**
3:10 p.m. – 4:00 p.m.	**Non-contact On-wafer Probing for mmW and THz Applications: Concept, Implementation, and Performance** *Kubilay Sertel - TeraProbes, Inc., and The Ohio State University*
4:00 p.m. – 4:50 p.m.	**On-Wafer System Calibration for mm-Wave Frequency Applications** *Andrej Rumiantsev - MPI Corporation* *Marco Spirito – Delft University of Technology*
4:50 p.m. – 5:00 p.m.	**'Bring your problem' -** *All instructors*

Day 2

8:00 a.m. – 8:50 a.m.	**Applications of the NIST Microwave Uncertainty Framework** *Jeffrey Jargon – NIST*
8:50 a.m. – 9:40 a.m.	**Multi-Physics Measurements and Modeling** *Peter Aaen – Colorado School of Mines*
9:40 a.m. – 10:10 a.m.	**Break**
10:10 a.m. – 11:00 a.m.	**Everything You Can Do With Vector Nonlinear Microwave Measurements** *Patrick Roblin – The Ohio State University*
11:00 a.m. – 11:50 a.m.	**Introduction to X-Parameters** *Jan Verspecht - Keysight Technologies*
11:50 a.m. – 12:00 p.m.	**Wrap-up**

Contact

James C. Booth, NIST, Boulder, CO, USA (james.booth@nist.gov)
Short Course Coordinator

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ABSTRACTS

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1. Modern Network Analyzer 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.

2. 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.

3. High-speed oscilloscopes, what the manual doesn't tell you

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.

4. On-Wafer Materials Measurements

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.

5. Fundamentals of On-Wafer Measurements

Dylan Williams – NIST

This presentation will cover the fundamentals of on-wafer measurements. It will start with microwave equivalent circuit theory and what the thru-reflect-line calibration measures. Then it will focus on accurate on-wafer calibrations in lossy printed transmission lines that derive directly from the microwave equivalent circuit theory.

6. Traceable On-Wafer Measurements at mm-Wave Frequencies

Uwe Arz – Physikalisch-Technische Bundesanstalt (PTB)

Recently, PTB established traceability for multiline TRL calibrations using selected combinations of substrate materials, coplanar waveguides and probes. The talk will elaborate on the methodology used for the uncertainty budget, which includes instrumentation errors such as noise, drift and cable effects but also repeatability errors and uncertainties in the calibration standards. Then, we will demonstrate how the uncertainties obtained for reference multiline TRL calibrations can be transferred to industrial applications using e.g. fixed-probe-distance calibrations such as SOLT. Key is the proper characterization of the transfer standards, which can be located on commercial impedance standard substrates, with a custom-made, application-specific reference calibration.

7. Non-contact On-wafer Probing for mmW and THz Applications: Concept, Implementation, and Performance

Kubilay Sertel - Associate Professor, Electrical and Computer Engineering Department
The Ohio State University, and President, TeraProbes, Inc.

This lecture will present the operating principles and the performance of a new class of on-wafer probing method based on non-contact, quasi-optical coupling of test signals onto the test wafer through monolithic planar antennas and an extended hemispherical lens. Developed as an alternative to conventional probes that rely on electrical contact with the test device, non-contact probing eliminates key shortcomings such as contact repeatability and durability. Effective coupling of the test signals onto the test wafer is achieved using simple yet wideband, slot-based antennas that are monolithically fabricated to replace the conventional probe landing pads. A 2-port quasi-optical link is formed between the frequency-extender flanges and the on-wafer reference planes at the test device ports through a single high-resistivity Silicon lens. The system can be treated as an open-fixture and can be calibrated for accurate and repeatable measurements without damaging the test wafer. Details of the setup, as well as on-chip non-contact calibration methods, system repeatability and several examples including pure-differential mode testing beyond 100GHz will be presented at the short-course.

8. On-Wafer System Calibration for mm-Wave Frequency Applications
Andrej Rumiantsev - MPI Corporation
Marco Spirito – Delft University of Technology
The accuracy of the wafer-level calibration procedure mm-wave is hindered by several effect, such as the effect of calibration transfer from the calibration substrate to the DUT environment, the effect of unwanted modes propagating in the substrate and the probe to probe cross talk.
Properly being able to define correctly the calibration reference planes, selecting the optimal calibration technique and designing standards that can be integrated in the same environment of the DUT allows to dramatically increase the accuracy and repeatability of the calibration procedure, resulting, ultimately with improved data for model extract or device optimization. Several of the challenges and the state of the art solution to overcome them will be explain and discussed during this short course.

9. Applications of the NIST Microwave Uncertainty Framework
Jeffrey Jargon – NIST

In this presentation, we will provide an overview of the NIST Microwave Uncertainty Framework, a software package that allows users to represent, propagate, and estimate correlated uncertainties for many different microwave measurement paradigms and systems including vector network analyzers, oscilloscopes, and vector signal analyzers to name just a few. Correlated uncertainty analysis preserves correlations or structure in measurement records and allows us to propagate uncertainties through transformations by providing consistent uncertainties in various domains, such as mappings between time and frequency.

The Microwave Uncertainty Framework utilizes parallel sensitivity and Monte-Carlo analyses. Sensitivity analysis is accurate for linear transformations and assumes Gaussian or Student-T distributions and are efficient as only a single computation is required for each base quantity. In contrast, Monte Carlo analysis can handle nonlinear transformations and complicated probability distributions, however it can be computationally expensive as it requires numerous samples to accurately represent the distributions. In addition to the overview, we will present several application examples, including calibration of vector network analyzers, measurement of error vector magnitude, design of power amplifiers, and determination of random uncertainties from repeated measurements.

10. Multiphysics Measurement of Microwave Circuits Under Realistic Operating Conditions
Peter Aaen – Colorado School of Mines

Microwave circuits, especially power transistors, are essential components of mobile communication as they amplify signals to be transmitted wirelessly from the base-station to subscriber terminals. Their compact design is increasingly difficult, as mobile network operators require operation at higher output power and frequency while simultaneously demanding a reduction in the circuit size. Shrinking the device and increasing operational frequency results in significant internal electromagnetic coupling and increased power results in higher temperatures, both of which are detrimental to performance -- the device physics, electromagnetic fields, and distributed temperatures co-couple to limit the overall efficiency. The presentation will discuss recent activities to develop new measurement methodologies to quantitatively visualize the internal operation of the device while they operate under realistic conditions. These new techniques provide vast new amounts of data and insight that will enable future high efficiency semiconductor device designs

11. 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.

12. Measuring Amplifier Modulation Distortion using a Vector Network Analyzer

Jan Verspecht - Keysight Technologies

This paper describes a new method to characterize signal distortion caused by high-frequency amplifiers under large signal modulated operating conditions. The method uses a combination of a vector network analyzer and a vector signal generator. The method is based on the decomposition of the response signal into one part that is linearly correlated with the stimulus signal, and another part that is the nonlinear distortion. The decomposition is performed by calculating the statistical cross-correlation between the measured spectra of the stimulus and the response signal. The stimulus signals are repetitive and are designed to match the statistical and spectral characteristics of any given modulation format. The method provides a way to measure error-vector-magnitude solely based on the device behavior, without the need for demodulation. This makes the method a good candidate for traceable EVM measurements of active components. The method returns both EVM and the frequency response function associated with the best linear approximation model of the component under a realistic broadband modulated stimulus signal.

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Lecturer Bios:

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.

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.

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.

Dr. Booth is a member of the American Association for the Advancement of Science (AAAS) and is active on two technical committees of the IEEE Microwave Theory and Techniques Society, including Biological Effects and Medical Applications of RF and Microwaves, and Microwave Superconductivity. He was the recipient of a Department of Commerce Bronze Medal in 2015 for the development and application of measurements to determine electrical properties of thin-film materials over a range of frequencies from a few hertz to the terahertz regime.

Dylan Williams (M'80–SM'90–F'02) received the Ph.D. degree in electrical engineering from the University of California at Berkeley, Berkeley, CA, USA, in 1986. In 1989, he joined the Electromagnetic Fields Division, National Institute of Standards and Technology, Boulder, CO, USA, where he develops electrical waveform and microwave metrology. He has published over 100 technical papers.

Dr. Williams was a recipient of the Department of Commerce Bronze and Silver Medals, the Astin Measurement Science Award, two Electrical Engineering Laboratorys Out- standing Paper Awards, three Automatic RF TechniquesGroup (ARFTG) Best Paper Awards, the ARFTG Automated Measurements Technology Award, the IEEE Morris E. Leeds Award, the European Microwave Prize, and the 2013 IEEE Joseph F. Keithley Award. He also served as an Editor for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES from 2006 to 2010 and the Executive Editor of the IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY.

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 until 2018 he has led the European EMPIR project PlanarCal as coordinator. He is currently head of the Working Group Fundamentals of Scattering Parameter Measurements at PTB.

Uwe 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 Awards and two ARFTG Best Paper Awards. In 2011, he was coauthor of the paper which was awarded the European Microwave Prize.

Uwe served as Program Chair of the 69th ARFTG Conference and as Co-Chair of the IEEE SPI Workshop (2004 to 2006 and 2010). From 2003 to 2011, he was a member of the ARFTG Executive Committee. Currently he is a member of the SPI Standing Committee, of the MTT-S Technical Committee on Microwave Measurements MTT-11 and of Germany's URSI Commission A (Electromagnetic Metrology).

Kubilay Sertel is an Associate Professor at the Electrical and Computer Engineering Department at the Ohio State University and the Founding President of TeraProbes, Inc. He received his PhD in 2003 from the Electrical Engineering and Computer Science Department at the University of Michigan-Ann Arbor and was an Assistant Professor from 2012-2017. During 2003-2012, he was a Research Scientist at the ElectroScience Laboratory. His current research focuses on the analysis and design of THz and mmW sensors and radars, on-wafer non-contact metrology systems for device and IC testing, biomedical applications of THz imaging, as well as spectroscopy techniques for non-destructive evaluation. His research interests also include RF/mmW ultra-wideband low-profile phased arrays for cognitive sensing and opportunistic wireless networks, reconfigurable antennas and arrays, applied electromagnetic theory and computational electromagnetics, particularly, curvilinear fast multipole modeling of hybrid integral equation/finite element systems and efficient solution of large-scale, real-life problems on massively parallel supercomputing platforms.

Prof. Sertel is a Senior Member of IEEE, member of IEEE Antennas and Propagation and Microwave Theory and Techniques Societies and an elected member of URSI Commission B. He is a Fellow of Applied Computational Electromagnetics Society. He is also the Editor-in-Chief for Electronic Publications for the IEEE Antennas and Propagation Society. He co-authored two books: Integral Equation Methods for Electromagnetics (SciTech Publishing, 2012) and Frequency Domain Hybrid Finite Element Methods in Electromagnetics (Morgan & Claypool, 2006), 6 book chapters, 4 patents, and published over 80 journal papers and more than 300 conference articles.

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 were he held various engineering product management and marketing positions. He significantly contributed to the development of the RF wafer probe, the |Z| Probe, wafer-level calibration standards, calibration software and probe systems. From 2010 to 2013 he was Product Marketing Manager of Device Characterization for Modeling and Process Development at Cascade Microtech and responsible for Elite300 system product line. 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), TPC member of BCICTS, past Technical Program Chair of ARFTG-92nd and ARFTG-93rd and the General Chair of ARFTG-94th. 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”.

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.

Jeffrey Jargon received his Ph.D. degree in electrical engineering from the University of Colorado at Boulder in 2003. He has been a Staff Member of the National Institute of Standards and Technology (NIST), Boulder, CO, since 1990 and has conducted research in the areas of vector network analysis, optical performance monitoring, and waveform metrology. He was the recipient of an URSI Young Scientist Award and a Department of Commerce Silver Medal Award, and is also a Senior Member of IEEE, a registered Professional Engineer in the State of Colorado, an ASQ Certified Quality Engineer, and has been a longtime contributor to ARFTG.

Peter H. Aaen received the B.A.Sc. degree in engineering science and the M.A.Sc. degree in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 1995 and 1997, respectively, and the Ph.D. degree in electrical engineering from Arizona State University, Tempe, AZ, USA, in 2005. He was the Manager of the RF Division, RF Modeling and Measurement Technology Team, Freescale Semiconductor, Inc., Tempe, AZ, USA, a company which he joined in 1997, then the Semiconductor Product Sector, Motorola, Inc. In 2013, he joined the Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, U.K., where he was a Reader of microwave semiconductor device modeling. He was also the Director of the Nonlinear Microwave Measurement and Modeling Laboratory, a joint University of Surrey/National Physical Laboratory, and the Director of National Physical Laboratory, Teddington, U.K. In 2019, he joined the Colorado School of Mines as a Professor and Head of the Electrical Engineering Department.

He has co-authored Modeling and Characterization of RF and Microwave Power FETs (Cambridge University Press, 2007). Dr. Aaen is a member of the Microwave Theory and Techniques and Electron Device Societies, an Executive Committee Member and Vice-President of the Automatic RF Techniques Group, and formerly was the Chair of the IEEE Technical Committee (MTT-1) on Computer-Aided Design.

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.

Jan Verspecht received his Ph.D. degree from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1995. He started his career as a research engineer with the Hewlett-Packard Company, later 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). In 2012 VTD was acquired by Agilent Technologies, now Keysight Technologies, where he holds the position of Master Research Engineer.

Dr. Verspecht invented X-parameters. His research interests are large-signal characterization and behavioral modeling of RF and microwave components. He holds 16 patents and has authored and co-authored 2 books, over 40 conference papers and 12 refereed journal papers.

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.