ARFTG-100th Microwave Measurement Symposium

MEASUREMENT CHALLENGES FOR EMERGING RF-TO-THZ TECHNOLOGIES

January 22nd-25th, 2023

Conference Program

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ARFTG Sponsors

ARFTG-100th Executive Committee would like to thank our sponsors for their great and valued support of the conference and the ARFTG organization.

Gold Sponsor

Silver Sponsors

Welcome to 100th ARFTG
Microwave Measurement Symposium

As Chair of the 100th ARFTG Microwave Measurement Symposium, which is co-located with Radio Wireless Week (RWW), I would like to welcome our attendees, speakers, and organizers. The organizers have worked throughout the last year to bring you this program, and we have some exciting speakers covering a wide range of topic from test challenges of RF modules to over-the-air testing at millimeter-waves. The theme for this conference is Measurement Challenges for Emerging RF-to-THz Technologies, but we also have many other topics of interest to the measurement and metrology community. Along with the conference, we have a short course, workshop, two users' forums, and a joint panel discussion with RWW's PAWR conference.

It is also a pleasure to chair the 100th ARFTG conference, which is a significant milestone for ARFTG. ARFTG started as a network analyzer user-group and held its first conference in September 1972, which was called "ANA-ATE", for Automatic Network Analyzer – Automatic Test Equipment. It adopted the ARFTG name in 1974. Today, ARFTG is devoted to both cutting-edge and practical measurements in RF, communications, microwaves, millimeter-waves, and related fields. ARFTG gives you the opportunity to meet with the people that developed many of the measurement techniques that you use today.

I look forward to seeing you in Las Vegas and enjoying the in-person interaction that is the hallmark of an ARFTG conference. I hope that you will enjoy the presentations and find them enriching. Finally, I would like to thank our sponsors, exhibiters, and all the members of the conference steering committee for their work and support in preparing this conference.

Joe Gering, General Chair

Joe Gering
General Chair
Qorvo

Joel Dunsmore
General co-Chair
Keysight Technologies

Dominique Schreurs
TPC Chair
KU Leuven

Marc Vanden Bossche
TPC co-Chair
NI

Sunday, January 22nd, 8:00 am – 5:00 pm

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.

12:00 pm — 2:00 pm

Short Course Lunch Break

On-Wafer Measurements

2:00 pm — 5:00 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 8:00 am – 13:00 pm

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.

12:00 pm — 1:00 pm

Short Course Lunch

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.

ARFTG User's Forums

	NVNA Users Forum
9:00 am — 9:05 am	Welcome Patrick Roblin (The Ohio State University, USA) and Apolinar Reynoso Hernandez (CICESE, Ensenada, Mexico)
9:05 am — 9:15 am	Round table introduction of the attendees
9:15 am — 9:40 am	Wideband NVNA Built from a VNA-SA Dr. & Prof. Jean-Pierre Teyssier (Keysight Technologies, USA)
9:40 am — 10:00 am	Discussion Moderators: Patrick Roblin (The Ohio State University, USA) and Apolinar Reynoso Hernandez (CICESE, Ensenada, Mexico)
10:00 am — 10:10 am	Student questions Miles Lindquist, Patrick Roblin (The Ohio State University, USA)
10:10 am — 10:20 am	Research update Prof. Apolinar Reynoso Hernandez (CICESE, Ensenada, Mexico)
10:20 am — 10:25 am	Farewell

	On-Wafer Users Forum
10:30 am — 10:35 am	Welcome Macro Spirito (Delf University of Technology), Jon Martens (Anritsu), Andrej Rumiantsev (MPI Corporation)
10:35 am — 10:55 am	Discussion on Anritsu 220-GHz Single-Sweep VNA Moderator: Jon Martens (Anritsu)
10:55 am — 11:15 am	Discussion on Preliminary Experience with the Anritsu 220 GHz Single-Sweep VNA Moderator: Lei Li (Cornell University)
11:15 am — 11:35 am	Introduction of the THZ User's Forum Idea Jim Hwang (Cornell University)
11:35 am — 11:55 am	General Discussion on the THZ User's Forum Moderator: Jim Booth (NIST)
11:55 am — 12:00 pm	Farewell

Monday, January 23rd, 1:00 pm – 9:00 pm

Conference Opening

1:00 pm — 1:10 pm

Welcome to the 100th ARFTG Conference

ARFTG President: David Blackham

Conference Co-Chairs: Joe Gering, Joel Dunsmore

TPC Co-Chairs: Dominique Schreurs, Marc Vanden Bossche

Session I: On-wafer Measurements

Chairs: Andrej Rumiantsev, Joe Gering

1:10 pm — 1:40 pm

Invited: RF Front-End High-Performance Technologies and Test Challenges

Brad Nelson, Sr. Director Engineering RF and Analog Products (Qorvo)

RF front-end electronics have evolved into highly integrated multi-technology modules that utilize very high performance GaAs, GaN and silicon. This presentation will give an overview of important markets and associated technologies in mobile handsets, automotive, wireless infrastructure, WiFi, IOT and CATV applications. The test challenges and trends in each market will be emphasized.

Brad Nelson is a Senior Engineering Director at Qorvo and based in San Jose, CA. Before Qorvo’s recent split into three divisions, his team developed products for Base Station infrastructure, WiFi front end modules, Automotive, Broadband CATV Infrastructure, IoT System on Chip and Defense small signal markets. The products his team designed generated approx $500M in revenue per year. In the current structure of Qorvo, his team focuses on Base Station and Broadband infrastructure as well as Defense small signal.

1:40 pm — 2:00

I-1

A Differential Broadband Single-Sweep 70 kHz-220 GHz Wafer-Level System: First Calibration and Measurement Characteristics

Andrej Rumiantsev (MPI Corporation)*; Jon Martens (Anritsu); Steve Reyes (Anritsu)

Broadband network analysis measurements are increasingly needed in 4-port and differential contexts. A GSGSG probe design and system capable of 70 kHz-220 GHz single-sweep measurements are presented that show similar raw losses (VNA port to probe tip) and measurement repeatability characteristics to two port measurements. Intra-probe coupling may be playing an uncertainty role at higher frequencies and conversion to mixed-mode parameters shows changes in the repeatability statistics that may be related to correlations of the repeatability variances.

2:00 pm — 2:20 pm PST

I-2

Reduced Calibration Error Employing Parametrized EM models and DC Load Extraction

Ehsan Shokrolahzade (TU Delft)*; Carmine De Martino (Vertigo Technologies); Marco Spirito (TU Delft)

In this contribution we present an approach to reduce the error in probe level calibrations, arising from lumped load variations, due to process spread. First, full-wave EM simulations are employed to generate the nominal standard responses, then a parametric EM simulation of the load structure allows to generate a parametrized model to account for process variation. The approach is tested on impedance standard calibration substrates developed on 150mm Quartz wafer (400 µm thick), where the high fidelity of the lateral dimension of the fabricated structures allows to confine the reference load parametric variation only to the thin-film resistor conductivity. The DC load response measured during the calibration step allows to identify the specific response of the probed load from the parametric model, completely absorbing the eventual process variation and thus reducing the calibration error spread. A complete analysis using full-wave EM simulations accounting for process variation is presented together with a preliminary set of data up to 67GHz.

2:20 pm — 2:40 pm PST

I-3

Traceable Lumped-Element Calibrations up to 110 GHz on Commercial Calibration Substrates

Uwe Arz (Physikalisch-Technische Bundesanstalt (PTB))*; Gia Ngoc Phung (Physikalische Technische Bundesanstalt); Andrej Rumiantsev (MPI Corporation)

In this paper we report for the first time on progress towards establishing traceability for on-wafer measurements of planar devices using fixed-distance lumped-element calibrations on a commercially available coplanar calibration substrate. The uncertainty budget includes instrumentation errors, connector repeatability and calibration standard uncertainties. Preliminary results are shown for verification devices embedded in the commercial calibration substrate.

ARFTG Business Meeting

2:40 pm — 2:55 pm

Treasurer Report

2:55 pm — 3:00 pm

ARFTG ExCom elections

Coffee Break and Exhibition

3:00 pm — 3:10 pm

Introductions Exhibitors

3:10 pm — 3:40 pm

Exhibition

Session II: Nonlinear Measurements

Chairs: Patrick Roblin, Marco Spirito

3:40 pm — 4:00 pm

II-1

The Dynamic Gain Model

Jan Verspecht (Keysight Technologies, Inc.)*; Augustine Stav (Keysight Technologies, Inc.); Sam Kusano (Keysight Technologies, Inc.)

We propose a new behavioral modelling approach called the Dynamic Gain model. The inverse of this modelling approach can be used for digital predistortion. The approach is based on dealing separately with linear dispersion, nonlinear compression, and nonlinear memory effects. The approach is illustrated on a commercial LDMOS Doherty power amplifier.

4:00 pm — 4:20

II-2

Linking nonlinear distortion and a signal’s cumulative distribution function: a measurement-based approach

Sander De Keersmaeker (Vrije Universiteit Brussel)*

Driven by societal, economical and technological pressures, wireless transmitters are becoming increasingly complex to achieve high power efficiency. High power efficiency is mainly obtained by pushing the RF power amplifier (PA) further into its nonlinear operating regime, which inevitably increases the nonlinear distortion generated by the amplifier. It is theoretically known that these distortions depend on both the power spectral density (PSD) and the probability density function (PDF) of the modulated excitation signal. In this paper, we experimentally validate the dependency of the nonlinear distortion with the cumulative distribution function (CDF) of the excitation signal’s envelope. First, we propose a novel design strategy that can impose the power spectral density and cumulative distribution function of an IQ-modulated signal. Next, measurements are performed on a nonlinear power amplifier, which experimentally validate the dependence of the amplifier’s linearized behavior on the envelope’s cumulative distribution function.

4:20 pm — 4:40 pm

II-3

Experimental Validation of ASM-HEMT Nonlinear Embedding Modeling of GaN HEMTs at X-band

Miles Lindquist (Ohio State University)*; Patrick Roblin (Ohio State University); Nicholas C Miller (Air Force Research Laboratory); Devin Davis (KBR); Ryan Gilbert (KBR); Michael Elliott (KBR)

This paper presents the experimental results from a validation of a newly-developed nonlinear embedding model for the GaN ASM-HEMT model. An extracted ASM-HEMT model was used together with the nonlinear embedding model to synthesize on-wafer Class F operation at 10 GHz for a 150 nm 1W GaN HEMT. The embedding model provided a set of multi-harmonic terminations at the transistor's source and load, which were then applied to the physical transistor in an experimental setup. The transistor's performance with only the predicted load termination at the fundamental is compared with its Class F performance when terminated at the predicted fundamental, second, and third harmonic load terminations, as well as second harmonic source termination. A phase sweep of each harmonic termination is further used to verify that the terminations predicted by the embedding model are optimal. The transistor's PAE when terminated with the embedding model's predicted terminations reaches 71%, in close agreement to the model's PAE prediction at peak power.

4:40 pm
—
5:00 pm

II-4

A Comprehensive Large-Signal RF Test System for Advanced Acoustic Device Performance and Reliability Characterization

Divya Gamini (Qorvo)*; John Fendrich (Qorvo); Arthur Durham (Qorvo); Denny Limanto (Qorvo); Chris Money (Qorvo)

To measure, evaluate, and quantify the behavior, performance, and reliability of acoustic resonators and filters under large-signal operating and stressed conditions, we introduce a comprehensive large-signal test system combined with test and analysis capabilities suitable for enhanced characterization of acoustic devices. The system's test features include simultaneous small-signal analysis, pulsed DC testing, large-signal calibrated parameters including harmonics, fast raw power data, and infrared or optical imaging. This system allows device characterization to be performed over CW or pulsed RF power, temperature, stress frequencies, and source and load impedances to study the effects under different combinations of stress for performance comparison and reliability evaluation. The focus in this paper is on the large-signal measurement capabilities and implementations featuring a vector-receiver-based load pull approach augmented with capabilities for acoustic device evaluation and specifically demonstrated for SAW and BAW technology variants and products. The system and process presented is also suitable for other types of both passive and active devices.

Joint RWW/ARFTG Activity Program

5:30 pm
—
6:30 pm

RWW/ARFTG Reception

6:30 pm
—
7:30

PAWR/ARFTG Panel

ARFTG Awards Banquet

7:30 pm
—
9:00 pm

Awards Dinner Talk

The Story of the Telegraph and Transmission Line Engineering

Ed Godshalk (George Fox University)

Transmission lines, often referred to as Interconnects, are a major component in integrated circuits, printed circuit boards, and communications systems. This talk traces the formative years of electrical engineering and the evolution of transmission line design and theory that enabled a global communications network over 100 years ago. The lessons learned are still relevant today and enabled the modern circuit simulator.

The story begins with the invention of the "Victorian internet", the telegraph, generally regarded as the first practical use of electronics. This is followed by transatlantic telegraph cable, which some historians equate as the 19th century equivalent of landing a man on the moon. These systems were a catalyst for improved battery design, insulated wire, coaxial cable and using the earth as a conductor. The transatlantic cable gave engineers a rude introduction to the concept of the RC time constant, which had a detrimental effect on data rate. To examine this problem in detail, a physical multi-section lumped element model was constructed by the author to investigate the performance of the first transatlantic cable, and how the slow data rate was mitigated in later designs. Many great minds of the 19th century worked to understand and solve the telegraph data rate problem, resulting in the Telegrapher's equations that were later used to make long distance telephone service a reality. These equations are still used today in many circuit simulators to model transmission line properties. A goal of this talk is to remind us of origin of electrical engineering and appreciate some of the important discoveries that were made along the way.

Ed Godshalk has been an Electrical Engineer for over 40 years, including several startups, his own company, Tektronix and Maxim Integrated. While at Cascade Microtech (1989-94) he invented the world's first waveguide input wafer probe and the Air Coplanar Probe (ACP). During his 22 years at Maxim, from which he retired in 2019, he created the Electromagnetics Group, which made many notable contributions to the semiconductor industry. He has over a dozen issued patents and numerous articles.

In 2020 he was elevated to the grade of Fellow by the Institute of Electrical and Electronic Engineers (IEEE) "For the development of microwave on-wafer probing and measurement techniques" which helped to enable the development of microwave integrated circuits (ICs).

Ed is now the Engineer in Residence at George Fox University, and finds great pleasure in teaching the next generation of microwave engineers. He emphasizes the history and origin of technical ideas to help students innovate and have a deeper understanding of engineering.

In his younger days he was a climbing guide, and in 1993 he organized an expedition that successfully climbed Denali, in Alaska, the tallest peak in North America. n his retirement he restores vintage sports cars, enjoys backcountry skiing and being in the mountains.

ARFTG-99th Best Oral Paper

Traceable mmWave Modulated-Signal Measurements for OTA Test

Joshua M. Kast[1,2], Paritosh Manurkar[1,3], Kate Remley[1], Rob Horansky[1], Dylan Williams[1] ([1]National institute of Advanced Industrial Science and Technology, [2]Colorado School of Mines, [3]University of Colorado Boulder)

ARFTG-99th Best Student Paper	Local-Oscillator Third-Harmonic Injection for Improved Broadband Mixer Linearity Akim A. Babenko, Jon Martens (Anritsu Company)
ARFTG-99th Best Poster Paper	Determination of the Coplanar Waveguide Propagation Constant via Non-contact, On-wafer Measurements in WR1.5 Band Mitch Wallis[1], Charles Little[1], Richard Chamberlin[1], George Burton[1], Nathan Orloff[1], Christian Long[1], Kubilay Sertel[2] ([1]National institute of Advanced Industrial Science and Technology, [2]TeraProbes Inc.)
ARFTG-99th Best Exhibitor	KEYSIGHT TECHNOLOGIES
9:00 pm PST	**End of Monday's Conference Sessions**

Tuesday, January 24th, 8:00 am – 5:15 pm

Session III: Noise and Linear Measurements

Chairs: Jeffrey Jargon, Leonard Hayden

8:00 am — 8:20 am

III-1

Noise measurements in the presence of large signal transients and studies of recovery effects

Jon Martens (Anritsu)*

Noise behavior of devices and systems after large signal transients can reveal information about thermal, bias, trapping or hot electron behaviors as well as identify potential practical operational issues for receivers in a dynamic signal environment. A measurement configuration to study these effects is presented that is based on a low noise front-end isolated synchronously from the large signals and a wide-IF VNA platform that can capture the resulting noise behavior versus time. For noise floors that may be useful for studying power devices, ns to us scale resolution was achieved with repeatabilities and relative uncertainties on the order of 1 dB throughout the microwave frequency ranges for some practical noise levels.

8:20 am — 8:40 am

III-2

Frequency Converting Noise Receiver Calibration for Mixer Noise Parameter Extraction

Jonas Urbonas (Maury Microwave)*; Gary R Simpson (Maury Microwave)

Noise parameters are commonly used to design low noise amplifiers (LNAs), which are generally the first stage of a radio frequency receiver. If the LNA feeds directly into a mixer, the noise parameters of the mixer can significantly raise the overall noise parameters of the system. The extraction of mixer- based system noise parameters is complicated by the frequency conversion enabled by the mixer where the noise power on the input is at a different frequency than that on the output. This paper describes the setup, noise receiver calibration and extraction of mixer noise parameters. Additionally, challenges in low-frequency noise receiver calibration are described and illustrated using measurement examples.

8:40 am — 9:00 am

III-3

Empirical Study on the Validity of the Modal Separation Approach for Deembedding of Highly Asymmetrical Passive Differential Devices

Milan Rother (Technische Universität Braunschweig)*; Martin Maier (Technische Universität Braunschweig); Macej Wojnowski (Infineon); Vadim Issakov (Technische Universität Braunschweig)

Accurate on-wafer characterization of differential devices poses the challenge of de-embedding four-port error networks as a multimode problem. We have shown in our previous work that, under the assumption of negligible mode conversion, e.g. less than -30 dB, the 4x4 transfer matrix can be separated into two 2x2 matrices representing the differential and common-mode S-Parameters. This enables independent de-embedding of the two modes using classical two-port de-embedding techniques such as Thru-Line (TL) and Thru-Open (TO) which greatly decreases the complexity of the de-embedding problem. In this work, we compare the Multimode-Thru-Reflect-Line (MTRL) de-embedding technique to the classical two-port Thru-Reflect-Line (TRL) procedure including the pure-mode approximation. The MTRL technique performs true multimode de-embedding under consideration of all modal conversion terms and can be viewed as a theoretical gold standard for de-embedding of asymmetrical differential devices. We compare the two methods for the edge case of highly asymmetrical passive error networks to investigate further whether the modal separation approach / pure-mode approximation holds up to true multimode de-embedding. As an example, we characterize an on-chip transformer as the device-under-test (DUT) realized in 28nm bulk CMOS technology. Several asymmetric de-embedding structures were realized in the same process.

9:00 am — 9:20 am

III-4

Study on Measurement Discontinuity during On-wafer TRL Calibration of 28FD-SOI Devices up to 110 GHz

Karthi Pradeep (IMS Laboratory, University of Bordeaux)*; Sébastien Fregonese (IMS Laboratory, University of Bordeaux); Marina Deng (IMS Laboratory, University of Bordeaux); Benjamin Dormieu (STMicroelectronics, Crolles); Patrick Scheer (STMicroelectronics, Crolles); Thomas Zimmer (IMS Laboratory, University of Bordeaux)

This study analyses the effect of test structure design for on-wafer TRL calibration of 28nm FD-SOI MOSFETs upto 110 GHz. Two different calibration kits are designed with and without continuous ground plane and their effect on the extracted transistor parameters are studied in terms of the measurement discontinuities encountered. Measurement results are discussed in conjunction with electromagnetic (EM) co-simulations, which use the small-signal equivalent circuit model of transistor along with the 3D models of the probes and test structures. The electric field coupling between the probes is visualised in each case and conclusions are drawn.

9:20 am — 9:40 am

III-5

Extraordinary Permittivity Characterization Using 4H-SiC Substrate-Integrated-Waveguide Resonators

Lei Li (Cornell University)*; Steve Reyes (Anritsu); Mohammad Asadi (Cornell University); Xiaopeng Wang (Cornell University); Gianluca Fabi (Cornell University); Erdem Ozdemir (Cornell University); Weifeng Wu (University of Notre Dame); Patrick Fay (University of Notre Dame); James C. M. Hwang (Cornell University)

Currently, lacking suitable test structures, little data exist for the permittivity of hexagonal materials such as GaN and SiC at millimeter-wave frequencies, especially for the extraordinary permittivity $\varepsilon_{||}$ as opposed to the ordinary permittivity $\varepsilon_{\perp}$. This paper demonstrates for the first time that it is possible to characterize $\varepsilon_{||}$ of c-axis 4H SiC using on-wafer measurements of substrate-integrated-waveguide resonators. In fact, measurements on eleven resonators yield a relative $\varepsilon_{||}$ of 10.27 ± 0.03 and a loss tangent $\tan\delta < 0.02$ over the D band (110–170 GHz). The on-wafer measurements of resonators and other devices fabricated on the same SiC substrate can allow material property to be closely correlated with device performance. The present approach can be extended to materials of other types and orientations.

9:40 am — 10:10 am

Coffee Break and Exhibition

Session IV: Joint ARFTG/RWW Plenary Session

10:25 am
—
11:05 am

RWW
Plenary Talk

Microwave Acoustic Filters for Wireless Communications: Recent Developments and Innovations

Amelie Hagelaue, Professor (Technical University Munich), Co-Director of the Fraunhofer Research Institution for Microsystems and Solid-State Technologies

For 30 years the success of microwave acoustics, mainly in mobile phones, has been unstoppable. A lot of effort has been spent to reduce the number of SAW/BAW devices, or ideally, completely remove them. However, no competitive technology providing the same performance at the same size and cost exists today. Thus, the trend is going in the opposite direction, driven by the demand for ever higher data rates and the desire to use the same phone in all parts of the world. The number of acoustic wave devices in a mobile phone is increasing with each new generation of communication standards. In this talk recent developments and innovations for microwave acoustic filters are presented. Those developments are novel architectures, new materials and advanced modeling techniques.

Prof. **Amelie Hagelauer** received the Dipl.-Ing. degree in mechatronics and the Dr.-Ing. degree in electrical engineering from Friedrich-Alexander-University Erlangen-Nuremberg, Erlangen, Germany, in 2007 and 2013, respectively. In November 2007, she joined the FAU Institute for Electronics Engineering, where she researched on BAW resonators and filters toward her Ph.D. degree. Since 2013, she has been focusing on SAW/BAW and RF MEMS components, as well as on microwave integrated circuits for frontends. From 2016 to 2019, she had been leading a Research Group on electronic circuits and from August 2019 to September 2021 she was Full Professor at the University of Bayreuth, Germany. In September 2021, she has joined the Technical University Munich as Full Professor and became the Co-Director of the Fraunhofer Research Institution for Microsystems and Solid State Technologies EMFT.

She has been engaged in research and development of microwave theory and technology, electronic circuits and systems, and communication and sensing systems. In these fields, she has authored or coauthored more than 140 peer-reviewed publications. She acted as a Guest Editor for a special issue of the IEEE Transactions on Microwave Theory and Techniques on the topic RF Frontends for Mobile Radio and is now an Associate Editor of the IEEE Transactions on Microwave Theory and Techniques.

11:05 am
—
11:45 am

ARFTG
Plenary Talk

Future Trends in RF and Wireless Test Capabilities from 5G to 6G and Beyond

Charles Schroeder, NI Fellow (NI)

Measurements, and the science behind them, are key to the design of modern electromechanical systems. And while the devices we're designing are evolving rapidly, the instruments making these key measurements of performance have been slower to evolve. In general, the size of the instruments we all use hasn't changed in decades. And the internal architectures, still heavily reliant on PC-based hardware and software components, have reached their limits. It's time for a re-thinking, not just of the hardware and software architectures of instrumentation, but of how instruments are used as a part of the design process.

As an NI Fellow, **Charles Schroeder** works across the company on key business and technology-driven initiatives. He consults with executive leaders and department heads, including those from marketing, sales, and R&D, to drive the company's strategic direction, development, and future growth. With a focus on long-term innovation best practices and processes, he currently leads NI's efforts to find ground-breaking solutions to the test challenges introduced by the adoption of 6G and next-generation wireless technologies.

Since joining NI in 1995, Charles Schroeder has held various positions, including vice president of product marketing for RF and wireless communications and leadership roles across the RF, modular instruments, DAQ, and IMAQ Vision product lines. He holds bachelor's and master's degrees in electrical engineering from Texas A&M University.

12:00 pm — 1:00 pm

Lunch Break

Session V: Modulated-Signal Measurements

Session Chairs: Jean-Pierre Teyssier, Jon Martens

1:10 pm — 1:40 pm

Invited: Hierarchical Characterization of Antenna In Package Module at mmWave Frequencies and Beyond

J.-O. Plouchart, Research Staff Member (IBM T. J. Watson Research Center)

With the emergence of cost effective AiP mmWave phased-array for 5G, 6G, imaging, and satellite communication, complex characterizations are required to validate such systems. A hierarchical characterization methodology was developed for a 94GHz 64 AiP elements phased-array system, serving as example for other mmWave and possibly sub-THz frequencies. The hierarchical characterization and validation starts from direct antenna probing measurements on a fabricated package and with on-wafer measurements of sub-circuit to the final ASIC. Finally, the module is assembled into a characterization board where the software stack is developed to enable antenna chamber beamforming and beamsteering as well as over-the-air performance evaluation like static imaging or dynamic drone detection.

Jean-Olivier Plouchart pioneered and led the RF and mmWave SOI at the IBM Semiconductor Research and Development Center which is used in billions of mobile devices. He has published more than 125 papers with three most cited papers at RFIC conference. He also holds more than 80 patents. He is currently working as a Senior Research Scientist at the IBM T. J. Watson Research Center on 5G/6G mmWave phased array as well as circuits for quantum computers.

1:40 pm — 2:00 pm

V-1

VNA-Based Testbed for Accurate Linearizability Testing of RF Beamforming Arrays Under Modulated Signal

Nizar Messaoudi (Keysight Technologies, University of Waterloo)*; Ahmed Ben Ayed (University of Waterloo); Joel Dunsmore (Keysight Technologies); Slim Boumaiza (Nil)

This paper presents a vector network analyzer (VNA) based testbed for accurate phased arrays linearity and linearizability testing under wideband modulated signals. The proposed testbed relies on a standard horn based channel calibration to de-embed over-the-air receiver hardware frequency response and utilizes two of the VNA's receivers to simultaneously capture accurate representation of the array input and radiated signals. The testbed corrects the linear and nonlinear distortions exhibited by the transmitter underlying components (e.g., arbitrary waveform generator, up-converter, driver amplifiers, and couplers) as well as for the channel and receiver hardware frequency responses so that the linearizability testing is solely indicative of the performance of the array under test. Experiments conducted using an 8x8 RF beamforming array operated at 28 GHz confirmed the capacity of the proposed testbed to support digital predistortion based linearization testing under 5G NR 400 MHz OFDM test signal. More importantly, the precorrection of the linear and nonlinear distortions exhibited by the testbed yielded an improvement of the adjacent channel power ratios of the array radiated signal by up to 2-3 dB compared to the uncorrected case while using 48% less number of coefficients.

2:00 pm
—
2:20 pm

V-2

Improvements in 6G (D-band) Amplifier EVM Measurements using Clock-Locked Sources

Joel Dunsmore (Keysight Technologies)*; Jean-Pierre Teyssier (Keysight Technologies)

EVM measurements of amplifiers in sub-mm bands is a requirement for new 6G implementations. But limitations in signal generation quality, particularly phase noise, limits the ability to measure EVM and just as importantly, limits the ability to measure and correct distortion in sub-mm bands primarily due to phase noise of test equipment used in the measurement. Here we show a novel system using DDS derived sources which are all clocked from the same, high-performance, fundamental high-frequency clock. Derived from previous work on frequency converter measurements, this method provides a dramatic improvement in the ability to measure EVM, isolating the amplifier measurements from the phase noise of the test system. Examples in D-band and fully illustrated as well as extensions to G-band (220-320 GHz). Measurement results for several variations of systems are shown.

2:20 pm
—
2:40 pm

V-3

Iterative Calibration Method for Integrated Tunable mmW Vector-Sum Phase Shifter

Markku Jokinen (University of Oulu)*; Alok Sethi (University of Oulu); Olli Kursu (University of Oulu); Timo Rahkonen (University of Oulu); Marko E. Leinonen (University of Oulu); Aarno Pärssinen (University of Oulu)

An iterative calibration method of 5G mmW vector-sum phase shifter (VSPS) is presented in this paper. The phase and amplitude imbalances of I and Q branches can be tuned. The phase is adjusted with a tunable polyphase filter (PPF) by changing its resonance frequency. The VSPS is equipped with differential amplifiers on each branch which are used to compensate for the amplitude imbalance. The iterative calibration method uses information collected during the measurements and adjusts VSPS parameters towards the optimal operation point. The error vector magnitude (EVM) of VSPS phase constellation decreases fast along the iterations, and the calibration process can be finished with a fraction of the measurement time compared with exhaustive search. Results show that the method can reach an RMS amplitude error of 0.11 dB and phase error of 0.6 degrees on selected frequency points.

2:40 pm
—
3:00 pm

V-4

Recommended Practices for Calibrated Millimeter-Wave Modulated-Signal Measurements

Paritosh Manurkar (CU Boulder)*; Joshua M Kast (Colorado School of Mines); Dylan Williams (NIST); Rob Horansky (NIST); Dan Kuester (NIST); Kate Remley (NIST)

In a millimeter-wave modulated-signal measurement system with several calibration reference planes, we want the measured signal to be a close replica of the ideal signal at the reference plane which connects the near-ideal measured signal to subsequent applications, such as, over-the-air measurements. Recommended practices to transfer reference planes in such a situation are described here to ensure availability of a calibrated signal at the correct reference plane. Our work also highlights and demonstrates design choices to minimize the impact of receiver mismatch when using the calibrated modulated signal for subsequent applications.

3:00 pm — 3:40 pm

Coffee Break

Exhibition and Interactive Forum

Interactive Forum

Session Chairs: Joel Dunsmore, Dominique Schreurs

1:30 pm — 3:40 pm

P-1

Pulsed Time Domain Reflectometry for Microwaves and Acoustics

Charles M Jackson (Northrop Grumman Retired)*

This paper investigates pulsed time domain reflectometry and compares the technique for acoustics and microwaves. A pulse defined by a third derivative gaussian is generated by an AWG, arbitrary waveform generator. A broadband directional coupler is used to send the input, reflected, and through signals to a digital oscilloscope. The data is analyzed to find the S-parameters. Different approaches are compared.

1:30 pm — 3:40 pm

P-2

Tunable Distributed Feedback Laser Based Frequency Hopping in Terahertz Communications

Kathirvel Nallappan (Ecole Polytechnique de Montreal); Maksim Skorobogatiy (Ecole Polytechnique de Montreal)*

Terahertz (THz) spectrum (100 GHz-10 THz) is considered the next frontier in the design of high-speed wireless communication systems. While the high-power THz sources have commercially become available, it increases the possibility of developing THz jammers to disrupt the THz communication link. In this work, we present the photonics-based THz communication system and demonstrate the frequency hopping spread spectrum (FHSS) technique which acts against the single/multi-tone jamming attack in the frequency window of 110 GHz-170 GHz. We characterized the system and demonstrated the THz FHSS technique in a real-time communication system by transmitting a 6 Gbps NRZ signal in wireless link within the link distance of 1.75 m. We experimentally found that the measured bit error rate in the THz FHSS system is the time average of the measured BER for individual carrier frequencies within the hopping frequency window. By combining with the forward error correction codes and by using the tunable filter in the receiver, we believe that the proposed technique will offer a novel and compact solution against the single/multi-tone jammer for high-bit rate THz communications.

1:30 pm — 3:40 pm

Demonstration of TRL Calibration Performance on mmW PCBs using WSMP Connectors

P-3

Yagmur Ozturk (The Ohio State University)*; Niru Nahar (Ohio State University); Kubilay Sertel (Ohio State University)

We present, for the first time, the utility of Thru-Reflect-Line (TRL) calibration up to 100GHz on millimeter-wave printed circuit boards using next-generation WSMP connectors. A coplanar waveguide (CPW) TRL calibration kit is fabricated on Isola Astra MT77 substrate and raw measurements for 2-port scattering parameters of the calibration standards are recorded in two overlapping bands using two separate vector network analyzer (VNA) systems covering 40-67 GHz and 60-90 GHz (WR12), respectively. The 67GHz VNA is connected to the calibration kit ports using coaxial, 1.85mm-to-WSMP adapters and the WR12-band VNA is connected via waveguide flange to WSMP adapters, respectively. The validity and performance of the WSMP TRL calibration is demonstrated using a representative test device fabricated on the same substrate. We also compare the simulated and measured results to illustrate the effectiveness of WSMP connectors in 40-90GHz band. Since these connectors are very compact compared to existing 1mm-coaxial connectors, they can be particularly useful for high density designs and designs that require thin PCBs.

Session VI. OTA Measurements

Session Chairs: Basim Noori, Marc Vanden Bossche

3:40 pm — 4:00 pm

VI-1

A Deep Reinforcement Learning Approach for Automated Chamber Configuration Replicating mmWave Directional Industrial Channel Behavior

Mohamed Kashef (NIST)*; Sudantha Perera (NIST); Carnot Nogueira (NIST); Richard Candell (NIST); Kate Remley (NIST); Matthew Simons (NIST)

Industrial wireless channels have different characteristics than home and office channels due to their reflective nature. Moreover, the millimeter-wave (mmWave) wireless bands can play a big role in improving industrial wireless systems due to their large available bandwidth and the short wavelength that allows a large number of antennas to be located closely to each other. Wireless test chambers are used for over-the-air (OTA) testing and assessment of various protocols and equipment. However, in order to closely characterize a system under test, the chamber should be configured to replicate the environment where the system is deployed. In this work, we present a deep reinforcement learning protocol to configure a test chamber in order to replicate the spatial characteristics of measured mmWave channels in industrial environments. The proposed algorithm is general for any N-dimensional chamber configurations where it can be used to configure various reflectors, absorbers, and paddles inside a wireless test chamber.

4:00 pm — 4:20 pm

VI-2

Calibration approaches in Multi-Node Antenna Characterization Setups

Richard Coesoij (TU Delft)*; Ferry Musters (TU Delft); Daan Roos (TU Delft); Tycho van Velden (TU Delft); Marco Spirito (TU Delft)

This work presents calibration approaches aimed at mitigating the measurement error in multi-node over-the-air testbenches, arising from fluctuations in component responses and mechanical tolerances. The calibration approaches are detailed for the case of the Antenna Dome measurement setup previously presented by the authors.

In the current implementation, the Antenna Dome employs multiple dual linearly-polarized scalar sensing nodes, to enable real-time 2D (theta and phi) radiation pattern acquisition. The electrical response variation among the different sensing elements as well as their position

variation, with respect to the nominal value, due to the mechanical tolerances, introduce systematic error in the generated radiation patterns

Over-the-air procedures to linearize the power conversion asymmetry within a dual polarized node as well as the linearity response across nodes are described, presenting a reduction of the angular dependent error below ±0.5 dB across the various nodes. Moreover, to minimize the impact of mechanical deviations an over-the-air method is described to transfer the sensor coordinates from the mechanical reference to the antenna under test.

4:20 pm — 4:40 pm

VI-3

OTA Measurement Technique for Sub-THz Integrated Lens Antennas

Kimmo Rasilainen (University of Oulu)*; Marko E. Leinonen (University of Oulu); Mostafa Jafari Nokandi (University of Oulu); Jiangcheng Chen (University of Oulu); Klaus Nevala (University of Oulu); Timo Rahkonen (University of Oulu); Aarno Pärssinen (University of Oulu)

Moving to sub-THz frequencies introduces new challenges for wireless communications systems in terms of design, implementation, and testing. This paper presents a measurement technique for over-the-air (OTA) characterisation of sub-THz antennas at WR3.4 band (220–330 GHz), and a silicon (Si) lensfed by an on-chip antenna is used as a test vehicle. In the proposed measurement technique, the received sub-THz AM-modulated test signal is downconverted to kHz-range using a square-law power detector. Measurements and simulations/calculations are used to compare several key antenna/link parameters. Agreement between the results is good, which shows that the proposed technique provides a good and less hardware-intensive alternative for sub-THz antenna measurements.

4:40 pm — 5:00 pm

VI-4

Challenges in Measurement of Broadband THz Photoconductive Antennas

Zachary P Uttley (University of Arkansas)*; Jose Batista (University of Arkansas); Mahmudul Doha (University of Arkansas); Katie Welch (University of Arkansas); Hugh Churchill (University of Arkansas); Magda O El-Shenawee (University of Arkansas)

This work utilizes an open bench time-domain spectroscopy system to measure the THz pulse and spectrum of photoconductive antennas (PCAs) with two different active layer materials: low temperature gallium arsenide (LT-GaAs) and 2D black phosphorous (BP). COMSOL Multiphysics modeling of the PCAs has shown that using BP as an active layer greatly increases the optical to THz conversion efficiency compared to LT-GaAs. However, the fabrication and measurement of both devices has demonstrated the opposite.

5:00 pm — 5:15 pm

Conference Closing

Resume Business Meeting

Feedback Form

Info on the 101th ARFTG Conference

5:15 pm

End of ARFTG-100th Symposium

Wednesday, January 25th, 8:00 am – 12:00 pm

Workshop on Emerging millimeter-wave & THz measurement for 6G communication

Organizer: Masahiro Horibe, Former AIST

Chairs: Joe Gering (Qorvo), Jean-Pierre Teyssier (Keysight Technologies)

Millimeter-wave and THz technologies shall be mainstay technologies in 6G communications. These technologies also play a prominent role in RF, microwave, and millimeter-wave applications for 5G and 6G communications. This workshop will address some of the measurement challenges in millimeter-wave and THz frequency regions. It will start from a user's perspective with talks on the needs in measurement method and design for circuits and antenna devices. It will then shift to a measurement perspective with presentations on material characterization, silicon RF circuit and antenna, and calibration. Taken in entirety, this workshop will be an excellent resource for metrologists and RF circuit and system designers alike.

7:50 am — 8:00 am

Welcome

Workshop Chairs

8:00 am — 8:45 am

Overview of mmW & THz Measurement for 6G Communication

Roger Nichols (Keysight Technologies)

Abstract: The demand for higher data rates and capacity drives new generation of mobile wireless communications to explore and expand the use of new and additional spectrum. In this context, "New Spectrum" refers to spectrum that has *not previously been used for mobile (cellular) wireless communications*. "Additional Spectrum" refers to the incremental spectrum added to what has already been established for use by previous generations. These words may seem to refer to the same thing, but they have distinct meanings. New spectrum requires significant research and engineering to develop transceiver technologies to address the physical challenges of the new frequency and what is often a much wider bandwidth. Given today's crowded airwaves, Additional spectrum means incumbent users are impacted--sometimes with a glancing blow, sometimes with a knockout punch. As a design and measurement company, among our priorities and expertise is to enable the means for quantitative assessment of physical behaviors and radio is one particular focus. This presentation is an overview of how we see the move to 6G impacting the demand for spectrum from 100 to 400 GHz. It will then cover an overview of the measurement challenges we face for materials, radio channels, components, and systems including interoperability and co-existence.

Speaker's Biography: Roger Nichols' 37 years of engineering and management experience in wireless design and measurement at Hewlett-Packard, Agilent, and Keysight Technologies spans roles in R&D, marketing, and manufacturing. He has managed projects, programs, and departments beginning with analog cellular radio and on every subsequent standard evolving to 6G. He directed Keysight's 5G program starting in 2014 and has been directing Keysight's 6G program since its inception in 2019. He is a member of the FCC Technical Advisory Council and is also the director of Keysight's work in wireless standards. Roger holds a BSEE from the University of Colorado, Boulder

8:45 am — 9:30 am

Development of D-band Metasurface Reflectors for 6G: Material Characterizations over 100 GHz for Reliable Designs and Antenna Measurements for Performance Evaluations.

Yuto Kato (National Institute of Advanced Industrial Science and Technology, AIST).

Abstract: In this talk, I will present D-band metasurface reflectors at 140 GHz for the application of 6G communication coverage expansion. I will also talk about complex permittivity and conductivity measurement technique at millimeter frequencies for reliable reflector designs using a balanced-type circular disk resonator method, as well as antenna measurement technique for performance evaluations of the reflectors

Speaker's Biography: Yuto Kato received the B.S. and M.S. degrees in physics from The University of Tokyo, Hongo, Japan, in 2010 and 2012, respectively, and the Ph.D. degree from Osaka University, Toyonaka, Japan, in 2020. Since 2012, he has been with the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. His current research interests include material characterizations and electromagnetic metasurfaces at microwave and millimeter-wave frequencies

9:30 am — 10:15 am

Design of Silicon CMOS ICs and Modules for 6G: With Headaches, Possible Cures, and Open Questions in Measurements

Shuhei Amakawa (Hiroshima University)

Abstract: This talk will present 300-GHz-band silicon CMOS ICs and transmitter and receiver modules for high-speed wireless communications. It will also cover behind-the-scenes measurement issues, including some progress that was essential to the successful demonstration of the sub-THz transceivers, and remaining headaches that await treatment.

Speaker's Biography: Shuhei Amakawa received B.Eng., M.Eng., and Ph.D. degrees from the University of Tokyo in 1995, 1997, and 2001, respectively. He also received an MPhil degree in physics from the University of Cambridge. Since 2010, he has been with Hiroshima University, where he is currently a professor. His research interests include modeling and simulation of nanoelectronic devices and systems, design of RF circuits, and microwave theory and measurement. He currently serves as an International Technical Program Committee member of the International Solid-State Circuits Conference (ISSCC).

10:15 am — 10:30 am

Break

10:30 am — 11:15 am

Millimeter-wave and Terahertz Integrated Circuits to Enable Non-Linear Characterization above 100 GHz

Jerome Cheron (National Institute of Standard and Technology, NIST)

Abstract: Semiconductor foundries have developed technologies that operate above 100 GHz, enabling new and emerging applications. Instrumentation covering ultrawide bandwidths at these frequencies must be developed to accurately characterize the nonlinear response of active devices and circuits that are currently characterized using only linear scattering parameters and scalar power analyses.

We present and discuss new approaches to millimeter-wave high-precision sources, synthesizers, and on-wafer comb generators, with a focus on innovating InP monolithic integrated circuits designed to enable non-linear characterization above 100 GHz.

Speaker's Biography: Jerome Cheron received his Ph.D. degree in electrical engineering from the University of Limoges, France, in 2011. He joined the National Institute of Standards and Technology (NIST) in Boulder, in 2013. His current research interests include the characterization, modeling and design of millimeter-wave and terahertz active-circuits in III-V technologies.

11:15 am — 12:00 pm

Component Test under Modulated Signals for 6G Communication

Jean-Pierre Teyssier (Keysight Technologies)

Abstract: The upcoming 6G ecosystem at mm frequencies needs all the component test features we are used to at lower frequencies. Wideband modulated signal tests are the most demanding one, and the closest to devices real use.

The multi-ports coherent wideband spectrum analysis approach implemented into modern VNAs allows arbitrary wide vector signal analysis with phase consistency, opening the doors for frequency domain delta Error Vector Magnitude, and time domain Vector Signal Analysis (VSA) demodulation. The same coherent VNA measurement techniques can also be used for wideband source calibration and digital pre-distortion.

Speaker's Biography: Jean-Pierre Teyssier received the Master and Ph.D. degrees from Limoges University, France, in 1990 and 1994, respectively. From 1995 to 2012, he has been a Researcher and Professor with the XLIM Laboratory at University of Limoges, and he has been co-founder of the VTD (Verspecht Teyssier DeGroote) startup company in 2007. He is since 2012 a master research engineer with Keysight Technologies. He is currently the main engineer for the multi-port Spectrum Analyzer capability of the PNA-X VNA at Keysight. His recent contributions include the phase coherent mode of PNA-SA, the wideband phase stitching extended to mm wave frequencies, the PNA link to VSA for wideband signal demodulation.

12:00 pm

End of Workshop

ARFTG Executive Committee Election

ExCom Candidate Biographies

Chong Li

I am passionate on developing RF and microwave measurement techniques for both fundamental research and industry, especially on-wafer measurements. I have more than 30 peer reviewed papers and patents in the relevant fields. I am also enthusiastic about prompting measurement science to wider communities and I strongly believe ARFTG is the right platform. As a regular conference paper contributor and past TPC member of ARFTG, I have enjoyed my experience. However, I don't just want to "enjoy" it but contribute and serve to the conference and the group. Although having failed Four times in a row, I still want to campaign for the upcoming election with interests in the role of "Workshops and Forums" as I have accumulated enormous experience in these areas while being the Chair of Workshops and Short Courses of EuMW2021, London. Here below is my updated biography.

I am a Senior Lecturer in Electronics and Nanoscale Engineering and the Director of Electronic Systems Design Centre in James Watt School of Engineering, University of Glasgow, UK. Before re-joining Glasgow University in 2017, I was a Higher Research Scientist at UK's National Physical Laboratory (2014-2017) and a postdoc researcher at the University of Glasgow (2011-2014). My expertise includes on-wafer measurements, III-V semiconductor devices and micro-/nanofabrication.

I was the Group 4 (United Kingdom, Ireland, Gibraltar, Malta) representative to the European Microwave Association (EuMA) General Assembly between 2018 and 2021 and the Chair of Workshops & Short Courses, EuMW2021. I have served as a member of the technical programme committee for several conferences including ARFTG. I am a Member of IET, a Senior Member of IEEE and an Associate Editor of Royal Society Open Science.

David Blackham

David Blackham received his BSEE from Brigham Young University in 1979. He received his MSEM degree from Stanford University in 1985, he received his MSEE degree from National Technological University in 1991 and his Ph.D. from University of Leeds in 1999. David started working for Hewlett-Packard, in 1979 in R&D. David now works for Keysight Technologies. He has worked as an R&D engineer for microwave sources, RF and microwave vector network analyzers and microwave characterization of materials. David also spent a short time in production engineering responsible for scalar detectors and bridges. His work includes the development of algorithms and the software architecture for the implementation and support of vector error correction used in most Keysight vector network analyzers. He is also responsible for supporting the estimation of measurement uncertainties associated with Keysight vector network analyzers. He collaborates regularly with NIST and METAS on VNA calibration standards modeling, uncertainties, and verification.

He has published several papers in the dealing with microwave characterization of materials and vector network analyzers. He had been granted over a dozen patents on vector network analyzer calibration. He is currently president of ARFTG (Automatic Radio Frequency Techniques Group) and reviewer for the IEEE MTT journal. He is an active participant in many IEEE standards work groups related to connector standards and high frequency instrumentation performance verification guides.

Gia Ngoc Phung

Gia Ngoc Phung (Member, IEEE) received the Dipl.-Ing. and Ph.D. degrees from Technical University Berlin, Berlin, Germany, in 2012 and 2021, respectively. From 2013 to 2015, she was with Biotronik SE & Co. KG, Berlin, where she performed electromagnetic simulation of cardiac devices. From 2015 to 2019, she was with Ferdinand-Braun-Institut (FBH), Berlin, where she has worked on her Ph.D. thesis, mainly in the field of modeling and characterization of on-wafer measurements and microwave packaging at millimeter-wave frequencies. Since October 2019, she has been working with Physikalisch-Technische Bundesanstalt, Brunswick, Germany. Her main research interests are on-wafer and RF power metrology.

She was awarded the Young Scientist Award of the 2021 Kleinheubach Conference and was co-recipient of the 2011 European Microwave Prize.

Jeffrey A. Jargon

Jeffrey A. Jargon received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Colorado at Boulder in 1990, 1996, and 2003, respectively. 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, and an ASQ Certified Quality Engineer.

Jeffrey has been a longtime contributor to ARFTG, having authored or co-authored 34 conference papers since 1994, five of which have received best paper awards. He served as ARFTG's first Student Fellowship Coordinator from 1999 to 2003, and is currently serving on the ARFTG Executive Committee, where he works on e-Publicity. Jeffrey has served as the TPC Chair for the 96th ARFTG Conference, the TPC Co-Chair of the 97th Conference, the Chair of the 99th Conference, and the Co-Chair of the 101st Conference.

Marco Spirito

Marco Spirito: received the M.Sc. degree (cum laude) in electrical engineering from the University of Naples Federico II in 2000, and the Ph.D. degree in microelectronics from TU Delft in 2005. In April 2008, he joined the ELCA research group at TU Delft University where he has been an Associate Professor since April 2013. In 2010 and 2017, he was one of the co-founders of Anteverta-MW, and Vertigo Technologies, respectively.

Dr. Spirito received the IEEE Microwave Theory and Techniques Society Microwave Prize in 2008. He was a co-recipient of the Best Student Paper Award at the 2011 IEEE RFIC Symposium, the GAAS Association Student Fellowship in 2012, the Best Student Paper Award in second place at the 2018 IMBioC, the Best Paper Award at the 2019 Winter ARFTG Conference, and the Best Student Paper Award at the 2019 Summer ARFTG

Mauro Marchetti

Mauro Marchetti received the B.S. degree (cum laude) and the M.Sc. degree (cum laude) in electrical engineering from the University of Naples "Federico II," Naples, Italy, in 2004 and 2006 respectively, and the Ph.D. degree from Delft University of Technology, Delft, The Netherlands, in 2013.

In 2006 he joined the Electronics Research Laboratory, Delft University of Technology where he carried out his Ph.D. research on the development of advanced characterization setups for RF high-power and high-linearity amplifier design. 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 became Vice President of Engineering at Maury Microwave Corporation.

He is currently a member of the IEEE MTT-3 microwave measurements committee. His research interests include the development of advanced characterization setups for RF high-power and high-linearity amplifier design.

See you again at the ARFTG-101st Conference!

101st ARFTG Microwave Measurement Conference

Challenges in complex measurement environments

San Diego, California June 16, 2023

www.arftg.org

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CALL FOR PAPERS

The theme for the 101st ARFTG Conference (co-located with IMS 2023) is "Challenges in complex measurement environments" to help highlight the effects of the measurement media on the practices, technologies and results. Increasing flexibility of transmission systems and higher levels of device integration have increased the need for over-the-air or hybrid measurements as well as the need for better understanding of the measurement methods and the uncertainties involved. Similarly, high levels of integration have increased the complexity for on-wafer and fixtured analysis. We encourage the submission of original papers looking into the effects and practices needed for different environments as well as the recurring ARFTG favorites. Suggested topics include, but are certainly not limited to

- *On-wafer, over-the-air or hybrid measurements: methodologies, calibration approaches and related topics*
- *Calibration and uncertainty considerations in moving OTA measurements (robotics, stages, UAVs…)*
- *Nonlinear characterizations, incl. linearization, of devices, circuits, and systems*
- *De-embedding and calibration approaches for complex media*
- *Uncertainty topics in integrated system testing*
- *THz/mm-wave measurements, including with modulated signals*
- *Other developments in measurements and metrology*

DEADLINES

February 20, 2023	Electronic abstract/summary is due in PDF format.
March 20, 2023	Paper acceptance and classification will be communicated.
April 20, 2023	Publication-ready paper is due in PDF format.

Instructions for Authors

Instructions for authors are outlined briefly below. More details can be found on the ARFTG website: http://www.arftg.org/index.php/upcoming-conference/author-instructions. Authors are strongly encouraged to use the template on that webpage to prepare both initial summary and final paper submissions.

We request that authors submit a 4-page summary with supporting figures of both experimental setups and measurement results to enable evaluation with respect to the interests of the participants and the novelty of the work.

Contributed papers will be presented as 20-minute talks or in an interactive poster session. Final papers will be published as part of the ARFTG proceedings in IEEE Xplore, provided it has been presented at the conference.

Exhibit & Sponsorship

The 101st ARFTG Conference also offers outstanding exhibition and corporate sponsorship opportunities. Please contact our Exhibits Chair (Joel Dunsmore, exhibits@arftg.org) or our Sponsors Chair (Joe Gering, sponsorship@arftg.org) directly for further information.

IEEE ARFTG MTT-S

For more information on the next ARFTG-99th Conference, visit the conference web page.