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19-22 January, 2025
San Juan | Puerto Rico

CONFERENCE BOOK

104th ARFTG Microwave Measurement Symposium

Advanced Nonlinear and Linear Microwave Measurements

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Monday, January 20th

Afternoon Session

SESSION A: Loadpull and Nonlinear Measurements

A-1

13:10-13:35

KEYNOTE: Advancements in Transistor and Circuit Modeling for Next-Generation RF Circuit Design Techniques

Tony Gasseling (AMCAD, France)

In the fast-evolving landscape of 5G and 6G telecommunications, achieving optimal RF performance is paramount. This presentation delves into new strategies for transistor and circuit modeling that aim to replace conventional approaches. A key focus of this presentation is the introduction of a pioneering methodology for characterizing GaN HEMT technologies. Through precise measurement of the current-voltage (I-V) characteristic in non-50 Ω environments, the methodolgy presented unlock the ability to accurately model dynamic trapping states. By dynamically controlling the trapping state of charge using calibrated RF pre-pulses, derived from preliminary large-signal load-pull measurements, a new level of accuracy in transistor modeling is achieved.Moreover, leveraging these advanced transistor models, a novel Power Amplifier modeling flow at the circuit design stage is showcased. This innovative approach enables us to capture Power Amplifier behavior under diverse conditions, including instantaneous input power, carrier frequency, and load impedance variations. The insights gained from this modeling flow are invaluable for optimizing circuit performance, refining system design, and seamlessly integrating next-gen technologies.

Tony Gasseling is CEO and co-founder of AMCAD Engineering, a spin-off Company from the CNRS XLIM research laboratory created in 2004. He oversees all the company's business areas, and focuses his efforts on defining and implementing AMCAD's strategy and mission: "To help our customers develop safe, efficient and more environmentally friendly communication systems. His role is to lead a customer-focused company, as well as harnessing the skills of the people involved in the team to create tomorrow's measurement and RF circuit modeling solution for an enhanced simulation experience.

A-2

13:35-14:00

Invited: Characterization of GaN Transistors and PAs with Modulated Signals

Zoya Popovic (Univ. of Boulder, Colorado, USA)

An analysis of Gallium Nitride (GaN) transistor behavior and power amplifiers (PAs) under modulated signal excitation is presented. Using a passive load-pull system and a large-signal vector network analyzer with an Arbitrary Waveform Generator (AWG) wideband source, we characterize two 6W GaN-on-SiC transistors from different manufacturers under various excitations. Experimental results with 300-tone 6.1MHz bandwidth signals indicate that the power-added efficiency, output power, and gain of transistors with narrowband OFDM-like signals are sufficiently represented by their CW performance at the same mean power. Additionally, a PA is characterized with different numbers of 10-MHz multi-carrier signals, evenly spaced within a 500MHz bandwidth centered around a 4.35 GHz carrier. The single-stage hybrid GaN PA is designed with CW output power above 10W from 4 to 5 GHz and with PAE exceeding 50 percent from 4.1-4.6 GHz with a saturated gain above 8 dB at 28V drain bias. The efficiency, output power, noise power ratio, and spectral efficiency are quantified in measurement and show that the overall performance can be appropriately defined by an equally-weighted figure of merit which is a function of the number of modulated signals.

Zoya Popovic received the Dipl.Ing. degree from the University of Belgrade, Serbia, Yugoslavia, in 1985, and the PhD degree from the California Institute of Technology, Pasadena, in 1990. Since 1990, she has been with the University of Colorado Boulder, where she is currently a Distinguished Professor and holds the Lockheed Martin Endowed Chair in RF Engineering in the Department of Electrical, Computer and Energy Engineering. In 2001, she was a visiting professor with the Technical University of Munich, Munich, Germany. Since 1991, she has graduated more than 50 PhD students. Her research interests include high-efficiency, low-noise, and broadband microwave and millimeter-wave circuits, quasi-optical millimeter-wave techniques for imaging, smart and multibeam antenna arrays, intelligent RF front ends, and wireless powering for batteryless sensors. Popovic was the recipient of the 1993 and 2006 Microwave Prizes presented by the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) for the best journal papers, and received the 1996 URSI IssacKoga Gold Medal. In 1997, Eta Kappa Nu students chose her as a Professor of the Year. She was the recipient of a 2000 Humboldt Research Award for Senior U.S. Scientists from the German Alexander von Humboldt Stiftung. She was elected a Foreign Member of the Serbian Academy of Sciences and Arts in 2006. She was also the recipient of the 2001 Hewlett-Packard(HP)/American Society for Engineering Education(ASEE) Terman Medal for combined teaching and research excellence.

A-3

14:00-14:20

Rapid Characterization of the Impact of Dynamic Trapping on GaN HEMT IVs Using a Real-Time NVNA Lindquist

Miles Lindquist, Patrick Roblin, Matthew Nichols (Ohio State University, Ohio, USA)

This paper presents a novel testbed in which a pulsed real-time active-loadpull (pulsed-RTALP) measurement is performed before and after a class-B pulsed active-loadpull (pulsed-ALP) excitation to extract the IV curves of a transistor in less than a microsecond both before and after a pulsed class-B RF stress. The class-B ALP loadline is utilized in this measurement to provide a realistic way for the transistor to achieve a high instantaneous drain voltage in order to fill traps like is observed during moments of peak power in OFDM communication signals. The RTALP measurement is configured by driving the gate and drain of the transistor with signals at two different frequencies such that the resulting modulated loadline covers a large area of the transistor's IV space. A modulation frequency of 5 MHz is selected with 95 and 100 MHz gate and drain excitations for RTALP. The transistor's IV is then extracted from a single 200 ns period of the RTALP loadline. The RTALP and ALP measurements are performed with a real-time nonlinear vector network analyzer (RT-NVNA), enabling the capture of pulsed multiharmonic loadlines period-per-period and across 50 successive pulses. This testbed allows for the tracking of the evolution of the transistor's IV characteristics before and after each repeated pulsed class-B RF stress. By changing the pulse duty rate, a recovery time close to 4 ms is observed while the capture time is on the order of tens of nanoseconds. For a class-B RF stress with a 44 V peak voltage and a 25 V drain bias, the post-stress degraded IV characteristics is in good agreement after a single pulse with a pulsed-IV characteristics drain biased at 35 V.

A-4

14:20-14:40

Anomalous Behavior of Continuous Class-F Mode Power Amplifier

Daniel Alonso-Tejera, J. Apolinar Reynoso-Hernandez, Manuel Alejandro Pulido-Gaytan, Maria del Carmen Maya-Sanchez, Eduardo Antonio Murillo-Bracamontes, Jaime Sanchez-Garcia, Jose Raoul Loo-Yau (Cicese, Baja California, Mexico)

This paper presents the development of a fully calibrated low-frequency nonlinear vector network analyzer (LF-NVNA) and its application in the implementation of a time-domain low-frequency active harmonic load-pull (LF-AHLP) system. This setup enables the control of up to three harmonics and is employed to experimentally validate the theoretical framework and investigate low-voltage continuous class-F mode power amplifiers. Through the use of LF-AHLP, an anomalous large reverse gate current was observed by measuring the gate current waveform in low-voltage continuous class-F mode power amplifiers, using a packaged GaAs-MESFET power transistor, the FLK107MH-14 from Fujitsu, biased in class-B (VGS=-2.6 V; VDS=10 V; IDS $\approx$ 6 mA).

14:20-14:40

ARFTG Business Meeting

Rusty Myers (ARFTG President)

15:00-15:35

Coffee Break and Exhibition

Joel Dunsmore (ARFTG Exhibition Chair)

B-1

15:35-16:00

Invited: Trends in DUT Characterizations with Wideband Test Signals

Jean-Pierre Teyssier, Johan Ericsson (Keysight Technologies, California, USA)

Active component testing at sub-THz frequencies rely on the pertinent choice of instruments, test signals and data processing algorithms as the dynamic range margins of instruments are drastically reduced. In the meantime, the modulation bandwidths and data flows are larger than ever, often reaching 100GBits/s or more. Advanced measurement setups are pushed to their limits to do accurate and relevant DUT characterizations.

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 the inventor and currently the main engineer for the multi-port Spectrum Analyzer capability of the PNA-X. His recent contributions include the phase coherent mode of PNA-SA, the wideband phase stitching extended to mm wave frequencies, the PNA-X link to VSA for wideband signal demodulation.

B-2

16:00-16:20

Characterization and Correction of Homodyne Systems Enabling Single-Carrier 40 Gb/s in E-band

Talley Amir, Jan Verspecht, Sam Kusano (Keysight Technologies, California, USA)

Linear distortions in homodyne systems are caused by variations in amplitude gain, time delay, and phase between the in-phase and quadrature components of an input signal. In this paper, we offer a novel technique for correcting these imbalances at a system level. We offer a frequency-dependent characterization and correction procedure that supports high-frequency and wideband modulation signals at arbitrary resolution bandwidths. We demonstrate the application of our method by pre-distorting modulated waveforms transmitted through a 4-millimeter waveguide at E-band frequencies. Our results show that the received signals have a dynamic range of at least 40 dB, a large improvement over historical correction techniques. We assess our technique on 256-QAM constellations at 5 GBd (40 Gb/s) and measure 3.2 percent error vector magnitude, where comparable historical methods require various modifications in order to compare.

B-3

16:20-16:40

Piecewise Interpolation based Digital Predistortion of Power Amplifiers Across Wide Power Ranges

Nizar Messaoudi, Ahmed Ben Ayed, Slim Boumaiza (University of Waterloo, Ontario, Canada)

This paper introduces a novel piecewise linear interpolation scheme designed to enhance power amplifer (PA) linearity across a wide power range in MIMO systems. By interpolating between pre-determined digital predistortion (DPD) solutions, the proposed method reduces the complexity of the linearization process and eliminates the need for frequent retraining under varying operating conditions. Theoretical analysis and experimental validation on a Gallium Nitride (GaN) PA at 13 GHz to confirm the effectiveness of the scheme, achieving an Adjacent Channel Power Ratio (ACPR) better than -44 dB using just four sets of pre-trained DPD coefficients across a 17dB power range. With five training points, the method improves linearization to yield Error Vector Magnitude (EVM) beyond -40 dBc, significantly outperforming conventional single-point DPD techniques, which experience signal quality degradation of over 15 dB ACPR and EVM as output power fluctuates compared to DPD re-trained at every power level. This approach offers a scalable and efficient solution for maintaining high linearity and offers insight into how PA linearizability performance should be assessed in next-generation multi-antenna systems.

B-4

16:40-17:00

Comparative Study of Two Architectures Suitable for the Generation of Wideband Signals at Sub-THz

Zi Jun Su. Ahmed Ben Ayed, Slim Boumaiza, Patrick Mitran (University of Waterloo, Ontario, Canada)

This paper presents a comparative study of two architectures for generating wideband modulated signals at sub-THz frequencies using a frequency bonding approach, focusing on achievable output signal quality. The first architecture generates a wideband signal at an intermediate frequency (IF) and up-converts it to sub-THz frequencies using a heterodyne mixer. The second approach generates multiple narrowband signals at IF, up-converts each to sub-THz, and then combines them. The study shows that, under linear up-converter operation, both architectures achieve similar signal-to-noise ratios (SNR) and are limited by the noise floor. However, replacing the combiner in the second architecture with a frequency duplexer improves the SNR by 3 dB. At higher IF power levels, where up-converter nonlinearity becomes significant, both architectures require digital predistortion to mitigate distortion. Despite this, the second architecture demonstrates superior adjacent-channel power ratio (ACPR). D-band measurements confirm that the second architecture enhances ACPR by up to 8 dB at high IF power levels when generating a modulated signal with a carrier frequency of 142.5˜GHz and a modulation bandwidth of 1.2˜GHz, while performance at lower power levels remains comparable.

17:00

End of the ARFTG-104 First Day

Tuesday, January 21st

Morning Session

SESSION C: Millimeter-Wave Measurements

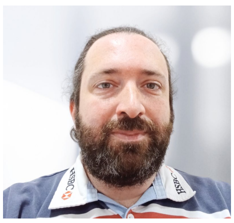
C-1

8:00-8:25

Invited: Paving the Way to Accurate mm-Wave NVNA Measurements

Alexander Baddeley, Paul Tasker, Roberto Quaglia (Cardiff University, Scotland, UK)

This paper summarizes the ongoing activities at Cardiff University to establish an accurate measurement setup for the characterization of mm-wave transistors in large signal conditions. The setup is a Nonlinear Vector Network Analyzer (NVNA) with a bandwidth of 100 GHz with passive tuners for source/load pull. The paper describes how the underpinning 67 GHz Vector Network Analyzer (VNA) was adapted to achieve single-sweep operation up to 110 GHz using frequency extenders and frequency diplexers, and the use of a 100 GHz oscilloscope for measuring the phase and reconstructing waveforms. The paper also discusses the adjustments made to the system and to the calibration procedure once it was realized that the main contributor to systematic errors was the mechanical perturbations that occur when changing the system configuration between the calibration states and the measurement state.



Roberto Quaglia received his PhD from Politecnico di Torino, Italy. After working for Huawei Technologies on some of the first mm-wave 5G prototypes, he joined Cardiff University with a Marie Sklodowska Curie Fellowship under Prof Cripps's supervision. He is now a Senior Lecturer at Cardiff University, where he leads the Centre for High Frequency Engineering, researching advanced power amplifier design and mm-wave characterisation and modelling.

C-2

8:25-8:45

Trends in DUT Characterizations with Wideband Test Signals

Bradley Thrasher (Nuvotronics, California, USA)

A test method with a novel test setup was developed to obtain a single-sweep 5-port probed s-parameter measurement of an 18-40 GHz Wilkinson power combiner. Recent commercialization of scalable vector network analyzers has enabled single-sweep characterization of multiport DUTs. On-wafer characterization of devices with 5+ ports has not been documented, as previous characterization efforts have used multiple reduced port measurements to obtain the full s-parameter matrix of the device. A novel test setup was required to land probes on the four input ports of this power combiner that were all oriented in the same direction. This paper will summarize the challenges and outcomes of this probed 5-port test setup of the 4-way power combiner DUT.

C-3

8:45-9:05

Probeable Microstrip Adapter Substrates Enabling Chip Testing Into D-Band

Hugo Morales, Larry Dunleavy, Chris DeMartino (Modelithics, Florida, USA)

This paper focuses on a new broadband thin-film probe adapter solution that enables accurate microstrip S-parameter measurements at frequencies extending into D-band. These low-loss alumina microstrip adapter substrates act as a convenient interface between RF/mm-wave coplanar ground-signal-ground (GSG) test probes and devices that may not be directly probeable with GSG probes. A calibration can be performed using a commercially available multi-line thru-reflect-line (TRL) microstrip calibration substrate that is directly compatible with the new adapter substrates. This paper presents high-quality device measurements up to 150 GHz that are made possible by the probe adapter solution. Measurements of broadband capacitors and a broadband resistor are shown to demonstrate the utility of the new adapter substrates

C-4

9:05-9:25

Affordable Frequency Extension for Wide Bandwidth mm-Wave Spectrum Analysis with a Lower Frequency VNA

Matthew J Nichols, Patrick Roblin, Nicholas Ellis (Ohio State University, Ohio, USA)

This paper presents a cost-effective measurement testbed to enable the use of a lower frequency vector network analyzer (VNA) as a multi-GHz vector signal analyzer (VSA) for modulated mm-Wave waveforms. We demonstrate various 80 – 640 MHz, 16 QAM signals generated with a carrier frequency of 40 GHz that are down-converted and demodulated. Digital post- distortion (DPoD) is used to perform the non-linear de-embedding of the down-conversion stage. Measurement of the testbed without the DUT yielded 0.30 percent error vector magnitude (EVM) and 5.48 percent EVM with a DUT. After DPoD, the DUT EVM is reduced to 1.19 percent at a 640 MHz symbol rate. This work demonstrates that a lower frequency VNA combined with a mixer can be used to realize an effective and affordable calibrated mm-Wave VSA, to acquire modulated signals with multi-GHz bandwidth.

C-5

9:25-9:45

Millimeter-Wave Implementation of Phased Array Emulation from Wideband Load-Pull Envelope Measurements

Mattia Mengozzi, Alberto Maria Angelotti, Alberto Santarelli, Paolo Mezzanotte, Gian Piero Gibiino (nan)

A measurement-based emulation procedure for phased arrays is implemented at millimeter-wave frequencies. By exploiting wideband active load-pull, it allows for the evaluation of the loading conditions and linearity performance of the power amplifier (PA) as operated in the array, without the need to manufacture the array itself. The technique is validated by emulating an ideal 1x4 linear array with variable coupling and an EM-simulated 2x2 patch array for an off-the-shelf PA.

9:45-10:10

Coffee Break and Exhibition

Joel Dunsmore (ARFTG Exhibition Chair)

10:10-11:50

ARFTG Plenary Talk: The convergence of Advanced Models and Measurements for Virtual Prototyping Success

Larry Dunleavy (MODELITHICS, INC.)

The electronic design automation (EDA) industry has become mature with time, frequency non-linear, electromagnetic and multi-domain simulation capabilities that are beyond anything envisioned a few decades ago. EDA advances are still being demanded and becoming available. An example is practical multi-physics simulations that promise to facilitate circuit, electromagnetic and thermal simulation needs in the same platform with a single 3D model description. The goal of all this capability is to predict, and optimize before building anything, future measured" real-world" behavior of a physical system or circuit with a virtual model, or digital twin of that system or circuit. The congruence of future measured behavior of a physical prototype, or product, to virtual prototype simulated behavior depends as much on the EDA tool capabilities as on the appropriateness and accuracy of the models used to represent the components within. Development of such models can take many forms depending on the type of component and type of simulations the models are to be used for. However, in most cases, accurate component-level measurements are essential for model development and/or model validation. In the end, virtual prototyping success comes down to intelligent use of accurate measurements at every stage of the process from model development and validation to closing the loop on the final measured behavior of the designed product. This talk will give an up-to-date summary of best practice RF/Microwave/mm-wave modeling strategies that include a range of different model types, and strategies, and how measurements are used in the process. Also to be discussed are examples of virtual prototyping success, where the ability to predict future linear, non-linear, noise and EM coupling effects is shown to be not only possible, but increasingly available to designers worldwide!

Dr. Larry Dunleavy co-founded Modelithics, Inc. in 2001, to provide improved modeling solutions and high-quality microwave and millimeter-wave measurement services for RF and microwave designers. He also is a Professor within USF's Department of Electrical Engineering, where he has been a faculty member since 1990. He is the Co-Director of the Center for Wireless and Microwave Information Systems (The WAMI Center). His teaching and research interests embrace all aspects of RF & Microwave circuit design, measurements, and modeling. In 1991 he enjoyed a summer research appointment at the Air Force Research Facility at Hanscom Field, MA. In 1997- 98 he spent a sabbatical year with the Noise Metrology Laboratory of the National Institute of Standards in Boulder, CO. Dr. Dunleavy also served as the General Chair and Co-chair of the 2014 IEEE MTT-S IMS held in Tampa Florida. Prior to joining USF, in the period from 1982 to 1990, he worked for E-Systems Company and Hughes Aircraft as an RF & Microwave design and test engineer. Dr. Dunleavy received the B.S.E.E. degree from Michigan Technological University in 1982 and the M.S.E.E. and Ph.D. degrees in 1984 and 1988, respectively, from the University of Michigan. He was a Howard Hughes Doctoral Fellow. Dr. Dunleavy is a Senior Member of IEEE and is active in the IEEE MTT Society and a Lifetime Member of the Automatic RF Techniques Group (ARFTG) and a founding member and serves on the Executive Committee for the IEEE WAMICON Conference held annually in Florida each year.

12:00-13:30 Awards Lunch

David Blackham (ARFTG Awards)

D-1

13:30-13:55

Invited: Impact of Uncertainty and Non-Idealities in On-Wafer Multiline TRL Calibration on Broadband GaN HEMT

Nicholas Miller (Michigan State University, Michigan, USA)

This paper analyzes the effect of broadband S-Parameter measurement uncertainty on small-signal modeling of millimeter-wave gallium nitride (GaN) high electron mobility transistors (HEMTs). Measurements from 0.5 – 110 GHz of two GaN HEMTs with different gate lengths are analyzed. An approach to quantifying the effect of measurement uncertainty on small-signal modeling is applied to the GaN HEMTs. The results indicate a strong dependence of the intrinsic model parameters to measurement uncertainty.

Nicholas C. Miller (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and computer engineering from Michigan State University, East Lansing, MI, USA, in 2013, 2015, and 2017, respectively. He was an Electronics Engineer at the Air Force Research Laboratory from 2017 to 2023. In 2023, he joined the Faculty of the Electrical and Computer Engineering Department, Michigan State University, as an Assistant Professor. His current research interests include linear and nonlinear mm-wave characterization of on-wafer transistors and integrated circuits, physics-based compact modeling of compound semiconductor transistors, and technology computer-aided design modeling of wide and ultrawide bandgap semiconductor transistors. Dr. Miller is currently a Young Professional Member of the IEEE MTT TC-3 Microwave Measurements Committee. He was a recipient of the IEEE AP-S Predoctoral Research Award in 2013, the U.S. DoD Science, Mathematics, and Research for Transformation (SMART) Scholarship in 2014, the IEEE Dayton Section Harrell V. Nobel Award in 2019 for physics-based device modeling, the Best Conference Paper Award at the 21st IEEE Wireless and Microwave Technology Conference (WAMICON) in 2021, the Best Presentation Award at the IEEE MTT-S Young Professional Workshop on Optimization and Modeling of Active Devices in 2022, and the AFRL Early Career Award in 2023.

D-2

13:55-14:15

Modal TRL De-Embedding of Symmetric Differential Transmission Lines with Proper Reference Impedance Matrix Transformations

Shuhei Amakawa, Takeshi Yoshida, Michael Gadringer, Wolfgan Bosch (University of Hiroshima, Japan)

Theory of mode transformation is presented for S-matrices and their associated reference impedances. It is shown that when an S-matrix is mode-transformed, the associated reference impedance matrix must also be transformed commensurately. Modal thru-reflect-line (TRL) de-embedding of 4-port symmetric differential transmission lines (TLs) is presented by way of example. It is shown that reference impedance matrices may become nondiagonal, which goes beyond the scope of the assumption made by the conventional S-parameter theory. The mode transformation theory is validated by using synthesized data via applying 2-port TRL and calibration comparison (for characteristic impedance estimation) to the two eigenmodes, followed by inverse mode transformation and renormalization transformation back to the single-ended nodal representation. Measurement data for differential TLs with GSGSG pads on a 65-nm CMOS chip are also presented.

D-3

14:15-14:35

Investigation of Probe Pitch Influence on On-Wafer Multiline TRL Calibrations up to 110 GHz

Gia Ngoc Phung, Uwe Arz (Physikalisch-Technische Bundesanstalt)

Recently, much progress has been made in the traceability of on-wafer measurements of planar devices on coplanar calibration substrates. However, reliable uncertainties for on-wafer S-parameters can only be given for a specific combination of substrate material, planar transmission line and probes, and only if single-mode propagation is ensured. This condition limits the use of uncertainties for probes with different dimensions. Therefore, this paper presents a systematic investigation of the influence of probe pitches on selected devices under test. The effects of probe pitch in conjunction with the influence of neighbourhood effects are investigated via simulations up to 110 GHz and compared with measurement results of example DUTs with expanded uncertainties at a coverage probability of 95 percent (k=2).

D-4

14:35-14:55

Method of Estimating RF Probe-Tip Calibration Reproducibility Budget on Commercial Calibration Substrates

Andrej Rumiantsev (MPI, Taiwan)

The demand for accurate, repeatable, and reproducible wafer-level RF calibration has significantly increased over the past decade. Engineers and researchers have invested substantial effort into improving the understanding of probe-tip calibration error sources, enhancing calibration standard designs, conducting cross-laboratory data comparisons, and, ultimately, establishing traceable calibration solutions. Despite significant advancements, several aspects of probe-tip calibration on commercially available substrates still warrant further investigation. One key area is the quantitative assessment of probe-tip accuracy variations across the calibration substrate. In this work, we introduce a method to decouple calibration errors due to the location of calibration standards from those caused by probe contact repeatability and drift. This approach enables more reliable and consistent comparisons of measurement data across different probe systems, even when using different models of the Vector Network Analyzer (VNA), as long as the system is calibrated with the same calibration method, using the same type of calibration substrate and wafer probes. Also, the proposed method simplifies application of the calibration uncertainty propagation software (e.g. VNA Tools from METAS) for wafer-level experiments. Furthermore, we illustrate how the estimated calibration reproducibility error budgets can be used for reporting the measurement results of a passive verification device.

14:55-15:35

Coffee Break, Interactive Forum and Exhibition

Joel Dunsmore (ARFTG Exhibition Chair)

E-1

15:35-15:55

Evaluation of On-Wafer Noise Parameter Measurement Techniques at Cryogenic Temperatures Kelly

James Kelly, Jing Wang, Afesomeh Ofiare, Chong Li, Nick Ridler (University of Glasgow, Scotland, UK)

In this paper, we highlight the current techniques for on-wafer noise parameter measurements under cryogenic conditions, and demonstrate their benefits and limitations. We first compared two noise parameter measurement systems at room temperature: one using the internal tuner of the network analyzer; and the other using an external tuner. We then used the internal tuner of the network analyzer for characterizing a GaN high electron mobility transistor at temperatures down to 78 K. The aim of this process was to identify which factors need addressing to improve the accuracy and precision of on-wafer noise parameter measurements at cryogenic temperatures. Stable noise data is reported up to 16 GHz; the minimum noise figure increased with both temperature and frequency, as expected. Predictions are also made for problems that may occur at lower temperatures, such as 4 K and mK.

E-2

15:55-16:15

Time-Domain Noise Characterization of LNAs: Validation, Trade-offs, and Analytical Insights

Ying Zeng (Chalmers University, Sweden)

We present a direct method for time-domain noise characterization of transient-state LNAs with ns-level resolution. We validate noise measurements using a time-domain method by comparing them with corresponding NFA-based data at a static reference bias. The trade-off between characterized noise variance and time resolution is investigated. A comprehensive analytical expression linking measured noise variance to noise source temperature and LNA static noise performance is derived. This provides insight for efficient and accurate measurements of transient noise and gain in noise-sensitive time-dividing systems.

E-3

16:15-16:35

Characterization of In-plane Polarization Domains in 2D SnSe by Scanning Microwave Microscopy

Yawei Zhang, Xiaopeng Wang, James C. M. Hwang, Nanna Mao, Peng Wu, Jing Kong (Cornell University, New York, USA)

Scanning microwave microscopy (SMM) allows nanoscale characterization of two-dimensional (2D) tin selenide (SnSe) polarization domain structure and resistance. This study examines SnSe flakes up to 15 nm thick, synthesized by low-pressure physical vapor deposition and transferred onto a silicon substrate. The SMM uncovers lateral polarization domains not detected by optical microscopy or atomic force microscopy. The SMM determines the resistivity of the domain interior is approximately 0.02 ·m, which is much higher than the resistivity of the domain boundaries. This observation agrees with I-V measurement of fabricated devices. This work demonstrates SMM's efficacy for non-destructive, in situ monitoring of 2D materials and devices.

E-4

16:35-16:55

Broadband Characterization of Flexible Conductor-Dielectric Composites

James Booth, Luckshitha Suriyasena Liyanage, Nathan Orloff, Nicholas Jungwirth, Sarah Evans, Christian Long, Angela Stelson (NIST, Colorado, USA)

Broadband measurements are important for characterizing a wide range of materials for communications applications at microwave and mm-wave frequencies. Here we report on broadband measurements of the effective permittivity of conductor-dielectric flexible composite materials over the frequency range 0.05 - 67 GHz. The materials under test are comprised of silver nanoparticles dispersed in an elastomer host material (polydimethylsiloxane) with variable volume fraction from 0.75 - 5.8 percent. Broadband calibration and de-embedding techniques are applied, along with finite-element simulations, to determine the complex effective permittivity for four different silver nanoparticle volume fractions from the measured scattering parameters. The resulting effective permittivity is well described by Maxwell-Garnett mixing formula, and the material coefficients extracted from fits include the conductivity, permittivity, and shape factor of the silver nanoparticle inclusions. Our analysis shows that as the filling fraction increases, the permittivity and conductivity of the inclusions increase dramatically, while the shape factor decreases. This results in much higher-than-expected enhancement of the effective permittivity for a range of volume fractions, which is likely due to aggregation or agglomeration of conducting particles in clusters with high interfacial polarizations.

17:00

End of the ARFTG-104 Conference

Interactive Forum Session

P-1

15:00-15:35

Application of Dual-Mode Ruby Dielectric Resonator for Characterization of Copper Foils in High-Frequency Circuits

Lukasz Nowicki[1], Tomasz Nalecz[1], Malgorzata Celuch[1], Thomas Devahif[2], Janusz Rudnicki[1] ([1]QWED Sp. z o. o, [2]Circuit Foil)

Achieving high electrical performance in mmWave PCBs often compromises copper foil reliability. This study introduces a novel measurement approach using Ruby Dielectric Resonators (RuDR) operating at 13 GHz and 21 GHz to assess copper foil conductivity without substrate interference. By focusing on direct loss measurements, these resonators provide accurate data on the effects of surface roughness on foil performance, crucial for 5G applications. The RuDR resonator, used in this study, highlights a decreasing exponential relationship between conductivity and surface roughness, confirming the significance of surface texture. The findings guide the development of high-performance materials for next-generation mmWave technologies.

P-2

15:00-15:35

Impact of Deep Memory in Identification of Quasi-Identical RF Power Amplifiers using Digital Post Distortion

Nicholas A Ellis, Patrick Roblin (Ohio State University, USA)

Quasi-identical power amplifiers (PA) can be differentiated through the unique non-linearities that are inherent to each individual PA. It was recently demonstrated that digital post distortion (DPoD) applied to the measured output data facilitates this PA identification. In this paper, a generalized cubic spline basis (GCSB) with selective deep memory is used to perform an enhanced DPoD. It is experimentally verified that the use of deep memory in the GCSB model can not only increase the performance of DPoD but also greatly magnify the differences observed in the normalized mean squared error (NMSE) of the linearized PA output signal relative to the reference input signal. This new technique can thus be used to reliably differentiate between two quasi-identical power amplifiers from the same device's manufacturer.

P-3

15:00-15:35

Multi-Band RF Characterization Test Setup for Millimeter Wave Applications

David Sardin, Jason Zhang (Qorvo, USA)

Abstract — This paper presents a versatile test setup configuration capable of reporting broadband large signal on-wafer characterization data over various frequency bands and up to 110 GHz. Millimeter wave characterization is often frequency band limited and requires various test hardware to be swapped when frequency focus evolves. Exploring various frequency bands is therefore time consuming as well as prone to measurement uncertainties addition when new measurement errors are introduced during the next calibration event. The presented coaxial test bench configuration allows measuring both small and large signal performance without the necessity to reconfigure the test hardware nor recalibrate the test bench. This work provides a descriptive overview of the test setup and discusses application by reporting measurement data of an E-band GaN power amplifier.

P-4

15:00-15:35

Techniques for Characterizing Dual-Input Outphasing Power Amplifiers

Dominic Mikrut[1], Yuhan Zheng[1], Patrick Roblin[1], Shane Smith[2], Josh Coffey[2], Ramy Tantawy[2] ([1]Ohio State University, USA, [2]SenseICs, USA)

The aim of this paper is to compare the usage of two different testbeds to characterize dual-input outphasing PAs which are becoming more prevalent. One testbed relies on the use of a legacy two-port nonlinear vector network analyzer (NVNA) and the second testbed relies on a four-port vector network analyzer (VNA). Two different dual-input outphasing PAs were characterized under CW conditions using the NVNA and VNA testbeds, respectively. The required procedures for each testbed for characterizing these dual-input outphasing PAs are presented and their relative merits discussed.

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15:00-15:35

Ultra-wideband Multi-line Calibration by Microstrip and Coplanar Impedance Standards on the Same GaAs Chip

Tianze Li, Lei Li, James C. M. Hwang (Cornell University, USA)

Calibration accuracy and stability have not been well studied above 100 GHz. This paper presents a comprehensive evaluation of multiline through-reflect-line (MTRL) calibration across an ultrawide bandwidth of 1-220 GHz using microstrip and coplanar impedance standards on the same GaAs chip. For the selection of impedance standards, different combinations of line lengths are evaluated in terms of normalized standard deviation and mean absolute error. The results show that increasing the number of lines significantly enhances accuracy and stability. This study affords valuable insights into the robustness of MTRL calibration across different impedance standards and offers practical guidance for ultra-wideband calibration.

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15:00-15:35

Optimization of a Near-Field Measurement System Based on Mechanically Modulated Scattering

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We build and optimize a prototype near-field mapping system that uses mechanically modulated scattering, focusing on standing wave suppression and probe design. We observe effects of standing waves in the apparatus, identify their root causes, then limit electric field distortions in the measured results. The validity of the system is benchmarked by measuring the magnitude and phase of the normal electric field radiated by a terminated microstrip line and comparing with the simulation.

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15:00-15:35

Human Free Automated Recalibration for Drift Compensation and Over Multiple Temperatures On-Wafer Autonomous RF Measurements

Pranav Kumar Shrivastava (FormFactor GmbH, Germany)

The Autonomous RF measurement assistant, a combination of programmable positioners, a precise digital microscopy system and advanced pattern recognition algorithms, enables fully autonomous, hands-free calibrations and measurements of RF devices over multiple temperatures. Autonomous RF is used to manage the entire test flow for thermal and ambient testing. This includes the full automated calibration, monitoring to prevent measurement drift, adjustment of probe spacing to account for growth and adjust probing geometries to deal with devices of different layout. In this work, the use of this approach with regard to doing MLTRL calibrations instead both off and on wafer. This work also shows interaction between WinCal, python and analytical approach to evaluate the calibration repeatability. Performance Analyzer discuss the repeatability and the probe placement for the unattended long duration RF measurements.