



## Millimeter-wave and THz Measurements

76<sup>th</sup> ARFTG, FALL 2010, Wednesday December 1, 1:15 PM – 5:00 PM, Clearwater, FL

**Topic:** This Workshop addresses challenges in measurements at millimetre-wave and THz frequencies and will cover topics from probe design to system-level measurements. Power measurements and network analysis are presented, along with several technological developments which enable fabrication of new types of components at high frequencies. Applications in remote sensing, biology, plasma diagnostics and radioastronomy will be discussed along with specific metrology needs for systems in this frequency range.

### Scheduled Speakers:

1:20pm – 1:25pm	Introduction, Prof. Zoya Popovic
1:25pm – 2:00pm	Dr. Richard Wylde
2:05pm – 2:40pm	Dr. Dylan Williams
2:45pm – 3:15pm	Prof. Bobby Weikle
3:15pm – 3:30pm	Coffee break
3:30pm – 4:05pm	Dr. Erich Grossman
4:10pm – 4:45pm	Dr. Kenneth Vanhille
4:50pm – 5:00pm	Conclusion, Prof. Zoya Popovic

**Organizer:** Prof Zoya Popovic, University of Colorado, Boulder, CO

**Zoya Popović** received the Dipl.Ing. degree from the University of Belgrade, Serbia, in 1985, and the Ph.D. degree from the California Institute of Technology in 1990. Since 1990, she has been with the University of Colorado at Boulder, where she is currently a Distinguished Professor and the Hudson Moore Jr. Endowed Chair in the department of Electrical, Computer and Energy Engineering. In 2001, she was a Visiting Professor with the Technical University of Munich, Germany. She has graduated 40 Ph.D. students and currently advises a group of 15 graduate students. Her research interests include high-efficiency, low-noise, and broadband microwave and millimeter-wave circuits, antennas and arrays, radar front ends, and wireless powering for batteryless sensors. Dr. Popovic is an IEEE Fellow and was the recipient of the 1993 and 2006 Microwave Prizes presented by the IEEE MTT Society for best journal papers, and received the 1996 URSI IssacKoga Gold Medal. She was the recipient of a 2000 Humboldt Research Award for Senior U.S. Scientists from the German Humboldt Stiftung, as well as the 2001 HP/ASEE Terman Medal for combined teaching and research excellence.

## Paper details

### **The design and use of THz quasi-optical systems for measurements covering the size range from $10^{-10}$ to $10^{37}$ metres**

**Author** Dr.Richard Wylde, Thomas Keating Ltd., The United Kingdom

**Abstract:** For the very highest performance measurement systems operating above about 100 GHz, we have long advocated quasi-optical approaches, which give very low loss, wide bandwidth and polarization agility not available with other circuit structures. By taking a wide range of application over  $10^{37}$  orders of magnitude (Size of the universe/size of a atom), the talk hopes to illustrate how particular QO techniques have been applied to solve measurement problems and how ideas in one area can cross-fertilise into other areas of instrument science. This talk will give some technical background to QO systems and give examples of their use in important measurement campaigns. Examples will come from

- Structural biology: St Andrews University's HiPER 1nS 1KW Electron Spin Resonance Spectrometer,
- Diagnostics in Plasma Fusion research for Energy production,
- Atmospheric remote sensing: JAXA's JEM/SMILES 640GHz BrO Probing SIS-based Radiometer and ESA's Cloud sensing pulsed Radar and
- Cosmic Microwave Background anisotropy measurements (including ESA's currently operating Planck mission),

**Dr. Richard Wylde** was educated at Eton and Sidney Sussex College, Cambridge, where he received the B.A. degree in Natural Sciences in 1979. He joined Queen Mary College, University of London, and received the Ph.D. degree in physics in 1985. He is a Fellow of the Institution of Engineering and Technology. He is currently an Honorary Reader in the School of Physics and Astronomy, University of St. Andrews, Scotland, and he manages both Thomas Keating Ltd. precision engineers, and QMC Instruments Ltd. His research interests lie in the design of THz systems for use in thermo-nuclear plasma diagnostics, observational cosmology, astronomy, electron-spin-resonance spectroscopy and atmospheric remote sensing.

### **Scattering parameter measurements in rectangular waveguide at THz frequencies**

**Author:** Dr. Dylan Williams, NIST-Boulder, U.S.A.

**Abstract:** This talk will address a discussion of strategies for accurate scattering-parameter measurements at THz frequencies and assessing uncertainties. We will discuss error sources and their mitigation, compare thru-reflect-line, thru-short-match, thru-short-radiating-open calibration approaches, and discuss the difficulties of estimating statistical bias and uncertainty in the measurements.

**Dr. Dylan F. Williams** received a Ph.D. in Electrical Engineering from the University of California, Berkeley in 1986. He joined the Electromagnetic Fields Division of the National Institute of Standards and Technology in 1989 where he develops electrical waveform and microwave metrology. He has published

over 80 technical papers and is a Fellow of the IEEE. He is the recipient of the Department of Commerce Bronze and Silver Medals, the Astin Measurement Science Award, two Electrical Engineering Laboratory's Outstanding Paper Awards, two Automatic RF Techniques Group (ARFTG) Best Paper Awards, the ARFTG Automated Measurements Technology Award, and the IEEE Morris E. Leeds Award. Dylan also served as Editor of the IEEE Transactions on Microwave Theory and Techniques from 2006 to 2010.

## **Integrated Schottky Diode and Micromachined-Based Components for Submillimeter-Wave Metrology**

**Author:** Prof. Bobby Weikle, University of Virginia, U.S.A.

**Abstract:** Advances in planar circuit fabrication technologies have revolutionized terahertz electronics by permitting the realization of integrated diode-based circuits and micromachined components resulting in systems with unprecedented levels of performance. Unfortunately, the state-of-the-art in test and measurement technology for terahertz systems has not kept pace and remains a major impediment to further progress. Ironically, although the high-performance devices and circuits that make terahertz metrology possible are currently being created, application of these to the development of a dependable measurement infrastructure is plagued by the lack of standardized transmission media, the absence of precision interfaces, and the need for accurate/repeatable calibration standards. This presentation will address these issues and describe recent efforts to develop a robust approach to scattering-parameter measurements at submillimeter wavelengths. Topics to be discussed include the implementation of six-port reflectometers, micromachined probes for on-wafer measurements above 300 GHz, and calibration approaches suitable for the submillimeter region.

**Prof. Bobby Weikle** received his Ph.D. in electrical engineering from Caltech in 1992. Following his graduate studies, he was a post-doctoral research scientist with the Department of Applied Electron Physics at Chalmers University in Göteborg, Sweden. In 1993, he joined the faculty of the University of Virginia where he is currently a Professor in the Department of Electrical and Computer Engineering. His current research interests include submillimeter electronics, high-frequency instrumentation and metrology, and quasi-optical techniques for millimeter-wave power combining and imaging.

## **Current Status of 0.1-1 THz Power Metrology**

**Author:** Dr. Erich Grossman, NIST Boulder

**Abstract:** "Absolute" radiometry, i.e. power measurement that is traceable to the SI, is well developed in the infrared and microwave frequency ranges, but undeveloped in the intermediate range from 100 GHz to 15 THz (20 micron wavelength). Commercial power meters developed for the IR or microwave ranges have historically been used with some success in the THz range, and in recent years, two additional power meters have been developed specifically for the THz band, and are now in widespread use. All are based on electrical substitution radiometry. We report here a campaign of intercomparisons between these power meters in the 100-1000 GHz range, and describe progress on relating these relative measurements to an

absolute power scale that is based on a filtered blackbody source with a well-established uncertainty budget.

**Erich N. Grossman** received an A.B. degree from Harvard College in 1980, and a Ph.D. from the California Institute of Technology in 1987, both in physics. His thesis work involved the construction and testing of an ultra-low noise, heterodyne receiver for 2.5 THz astronomy. From 1988 to 1989, he was a postdoctoral fellow at the Univ. of Texas at Austin, and in 1989, he joined the National Institute of Standards and Technology, Boulder, CO, where he is now a physicist in the Optoelectronics Division. His work at NIST focuses on infrared and submillimeter device physics. Notable accomplishments include the development and demonstration of the world's highest frequency, high efficiency lithographic antennas, the world's highest frequency Josephson junctions (awarded a Dept. of Commerce Gold Medal in 1993), and original conception and development of the SQUID multiplexer, enabling the first large arrays of ultralow-noise superconducting detectors. More recently, he has developed several 0.1-1 THz cameras for security applications. He is also chair of the Metrology Working Group for the DARPA Terahertz Electronics program.

## **Microfabrication of Rectangular Coax for Millimeter-Wave Frequencies**

**Author:** Dr. Kenneth Vanhille, Nuvotronics LLC., U.S.A.

**Abstract:** Emerging microfabrication techniques provides new possibilities for both improved performance and higher levels of integration for millimeter-wave applications. As one example, air-dielectric based rectangular coaxial transmission lines create true-TEM, low-loss, high-isolation microwave and millimeter-wave circuits. These circuits are similar to what has been created using stripline, however via fences are replaced by full-metal walls and the signal lines are suspended in air using periodic metal straps. In addition, for frequencies above W-band, complex, metal waveguide-based structures are also realizable. Topics to be presented include the fundamental properties of rectangular-coaxial based copper circuits for millimeter-wave applications and examples will be provided of devices that have recently been designed, fabricated and tested for such applications as low-loss millimeter-wave solid state power amplifier combining, and planetary landing radar.

**Dr. Ken Vanhille** has served as Member Technical Staff and Program Manager for Nuvotronics, LLC, Radford, VA, since 2007. During his tenure, he has led a variety of development and production programs for various government agencies and major defense contractors, including Ku-band antenna feed technology development, broadband solid-state power amplifiers from 4-18 GHz, and millimeter-wave (W and G-band) phased and frequency-scanned antenna arrays. Ken received his Ph.D. in Electrical Engineering from the University of Colorado at Boulder in 2007, and his BS degree in Electrical Engineering from Utah State University. He is a co-author of over a dozen publications in millimeter-wave component design, microfabrication, integration and packaging.