HIGH-FREQUENCY METROLOGY AT NIST: CURRENT PROGRAMS AND NEW DIRECTIONS

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Abstract: We provide an overview of the current state of high-frequency and microwave metrology programs at NIST, as well as a discussion of recent changes, emerging needs and exploratory new directions. A brief description of each of the core microwave metrology measurement services, (power, noise, scattering parameters, field strength, and antenna) is provided. Several of the newer programs, driven by needs which may lead to future measurement services, are also described.

1. INTRODUCTION

We will describe the main activities and current new efforts, after citing recent changes resulting from internal restructuring to improve efficiency. The NIST high frequency voltage services were previously carried out in both the NIST Boulder, CO laboratories (1 MHz – 1 GHz) and the Gaithersburg, MD laboratories (DC – 1 MHz). All of these services are now carried out at the Gaithersburg campus. The NIST 30 MHz attenuation calibration service has been transferred to the Army Primary Standards Laboratory in Huntsville, AL as the military was the main customer. Other mature services with decreasing demand such as two terminal low-frequency impedance calibrations and antenna-factor calibrations have been discontinued, as were some research programs. For example, while we study nonlinear properties where they arise, a program for developing a new formalism for non-linear device characterization was discontinued. We now describe our main measurement service activities.

2. BASIC MICROWAVE CALIBRATIONS:

Customers that use NIST microwave services include the electronics, communications, and aerospace industries, instrument manufacturers and other government agencies. We provide the fundamental microwave traceability that is essential for their needs and will continue to advance these programs. We also develop and disseminate recommended measurement and calibration methods, such as techniques for calibrating vector network analyzers (VNA). The following sections will briefly describe the basic microwave calibration services provided by the NIST Electromagnetics Division, the basic techniques employed and range of measurement values [1].

2.1 Scattering Parameters

Our s-parameter measurements and techniques support VNA calibration, traceability, uncertainties, VNA measurement process verification and VNA measurements. We use a variety of commercial VNAs as well as the NIST designed and developed Dual Six-port Network Analyzer Systems. Our calibrations are based on the LRL (line-reflect-line) calibration technique and generally use the NIST developed Multical program for calibration of the commercial VNAs [2].

Our measurements cover a large parameter space. We measure full complex s-parameters for one and two-port devices. Our capabilities span across 6 coaxial connector sizes: Type-N, 14, 7, 3.5, 2.92 and 2.4 mm and 7 waveguide sizes: WR 90, 62, 42, 28, 22, 15 and 10. The overall frequency range covered is 100 kHz to 110 GHz.

2.2 Power

A system's output power level is frequently the critical factor in the design, and ultimately the performance of RF and microwave equipment. The primary power standard used at NIST is the NIST designed micro-calorimeter. The calorimeter is used to calibrate our primary transfer standards which are thermistor type power detectors. Currently we have Type-N and 2.4 mm coaxial calorimeters and WR42, 28, 22, 15 and 10 waveguide calorimeters. Other coaxial sizes are measured through the use of calibrated adapters. Customer devices are measured on direct comparison systems or the six-port systems.

The power measurement services also cover a large range of frequencies and connector sizes. The power services measure the effective efficiency and calibration factor of power standards. We measure thermistor, thermoelectric and thin-film type power detectors. These services span across 5 coaxial connector sizes: Type-N, 7, 3.5, 2.92 and 2.4 mm and 7 waveguide sizes: WR 90, 62, 42, 28, 22, 15 and 10. The frequency range covered is 100 kHz to 96 GHz.

2.3 Noise

Noise is a limiting parameter in the performance of any electronic device or system. NIST noise–temperature measurements are performed on total–power radiometers, using two primary thermal noise standards, one of which is at ambient temperature and one of which is at cryogenic (liquid nitrogen) temperature. For measurements at 30 and 60 MHz, tunable coaxial standards are used. From 1 to 12.4 GHz, coaxial standards are used, and for 12.4 GHz and above, waveguide/horn standards are used. The NIST radiometers are double–sideband, total–power radiometers.

Noise temperature measurements are available for single–port, coaxial and rectangular waveguide noise sources under conditions of continuous, un-modulated operation. Measurement results on devices submitted with adapters attached, may apply only to the source plus adapter combination. For thermal noise, we provide calibration of coaxial noise standards at 30 MHz, 60 MHz, and from 1.0 GHz to 40 GHz. Waveguide standards are calibrated from 8.2 GHz to 65 GHz. We have recently added the capability to perform noise-parameter measurements on low-noise amplifiers.

2.4 Field Strength

Well-defined EM reference fields and transfer standards are necessary for establishing measurement traceability for the intensity of RF and microwave radiated signals. Regulation of EM-field levels for communications, for public health and safety, and for ensuring EM compatibility of radiating devices and products, are the main requirements for these services. Standard antennas; dipoles, log–periodic, monopoles, loop antennas, open–end waveguides, pyramidal horns and other antennas are used in conjunction with special EM facilities to generate standard electric fields for calibrating antennas and electromagnetic field probes over the frequency ranges covered. Measurements are made in TEM cells, on our Open Area Test Site or in the NIST EM Anechoic Chamber.

Standard electromagnetic fields are generated in TEM cells and used to calibrate electrically small antennas and antenna systems used for electromagnetic field probes in the frequency range 10 kHz to 300 MHz. The open area test site is used for special measurements, EMC experiments, and gain of antennas used in conjunction with field strength meters and electromagnetic field probes. Frequency ranges for different type of antennas include 25 MHz to 1000 MHz, 30 kHz to 300 MHz and 14 kHz to 50 MHz. The Anechoic Chamber is used for calibrating antennas and electromagnetic field probes. The normal frequency range covered in calibrations is 450 MHz to 40 GHz, and we can do 200 to 400 MHz with larger uncertainties.

2.5 Antenna parameters

Antenna measurements are critical in supporting the performance of satellite and other aerospace antenna systems, such as those associated with phased array, radar, and communication systems. High-gain antennas and probes are measured in the NIST antenna metrology scanning facilities. These facilities include two planar near-field ranges, a spherical and cylindrical near-field range, and an extrapolation range which provides on-axis probe gain and polarization characterization. Sets of precision standard antennas for which we have significant historical data are used as check reference standards. Near-field scanning metrology was pioneered at NIST and we continue to improve and extend the technology, theory and software.

Our services provide measurements of antenna gain, polarization and pattern. The frequency range for pattern measurements for large aperture antennas is 1.5 to 60 GHz on our large planar scanning facility. Gain and polarization measurements for such antennas are done on the extrapolation range, also from 1.5 to 60 GHz. A smaller planar scanning facility is used for smaller aperture antennas and (soon) higher frequencies. We also have a combination spherical-cylindrical scanning facility. In addition to occasional experimental research projects, this facility is mostly used to calibrate near-field scanning probes used on other near-field scanning facilities. These probes constitute NIST traceability for antenna calibrations at other ranges.

3. NEW DIRECTIONS IN HIGH-FREQUENCY METROLOGY

3.1 High-speed waveform measurement

The telecommuncations and information technology industries must continually advance their ability to deliver high-speed, reliable, and interoperable communication and information processing systems with greater information-carrying capacity and lower cost. Higher speeds and information capacities correspond to larger bandwidths and higher frequencies. Integrated digital and microwave electronics now used by industry require measurement bandwidths in excess of 110 GHz, larger than can be supported by current coaxial connector based microwave technology. Electro-optic information technology, microwave microelectronics, and digital is driving the need for reliable higher-frequency measurements to enable further advancements. The ultimate need is for the calibration of: high-speed sampling oscilloscopes, microwave mismatch-corrected sampling oscilloscopes, digital pattern generators, light-wave component analyzers, vector signal analyzers, vector signal sources, microwave transition analyzers, and nonlinear network analyzers (LSNAs). NIST has successfully performed well-characterized, mismatch-corrected, point-by-point waveform measurements to 200 GHz [3].

Technical Strategy: Develop a new 400 GHz on-wafer source and extend our on-wafer waveform measurement capability from 200 GHz to 400 GHz, based upon what we have learned with the present system. Build a 400 GHz opto-electronic waveform source, integrate this source into a microwave probe, and construct a new electro-optic sampling system to determine the bandwidth of this source, leading to 400 GHz on-wafer waveform standards and measurements. Develop a new joint time-domain/frequency-domain paradigm for high-speed coaxial waveform metrology. The key idea is to combine microwave mismatch correction with traceability to the electro-optic sampling system, and use that combination to establish a new paradigm in accurate waveform measurements to 110 GHz. Integrate other microwave instruments, such as samplers, power sensors, and six-ports, into microwave probe heads using our the 400 GHz bandwidth packaging technology we develop and construct flexible electro-optic sampling systems for performing measurements to 400 GHz on high-speed GaAs and silicon digital ICs.

Technical Accomplishments: NIST has previously developed and fully characterized an electro-optic sampling system which generates and accurately measures pulses on-wafer to 200 GHz. We have demonstrated this system’s capability of making accurate point-by-point measurements of high-speed waveforms up to 200 GHz with mismatch corrections and well characterized uncertainties. The theoretical and experimental results from this program have had a significant impact on waveform metrology and microwave characterizations of nonlinearities. These included demonstrating limitations to the commonly used nose-to-nose calibration techniques and the development of improved methods for calibrating nonlinear network analyzers. A leading European manufacturer of LSNAs now achieves traceability directly through the NIST electro-optic sampling system, and some high speed oscilloscope manufacturers have had reference oscilloscopes calibrated against it. We have also developed a new 110 GHz waveform measurement service traceable to our electro-optic sampling system, which includes correction for mismatches.

3.2 THz noise measurement

The rapid increase in research and technology development activities at terahertz frequencies has resulted in needs for accurate measurements and reference standards for critical parameters. Presently, no fundamental standards in the THz range exist for noise or power. The current drivers and applications for terahertz technology include biological spectroscopy, medical imaging, weapons detection, national security, earth resource remote sensing, and radio astronomy, as well as fundamental research. Some predict this technology is poised for rapid growth.

The objective of this program is to develop an accurate thermal noise-temperature measurement capability at terahertz frequencies, to provide fundamental physical standards for such measurements. Traceability to NIST noise standards at terahertz frequency would allow comparison of different measurements and meaningful comparison of performance of components and systems [4].

Technical Strategy: Develop a well-characterized variable-temperature terahertz source for use as a standard calibration target. Use the cryogenic detector and receiver developed by the NIST Terahertz Bio-imaging Project as a sensor. The receiver will be housed in a cryo-cooler instrumented for that purpose. The resulting radiometer can be used to characterize materials or components such as filters, as well as for measurements of the noise characteristics of components such as amplifiers, mixers, and quasi-optical adapters.

Technical Accomplishments: We have developed a method for very accurate measurement of the noise figure of cryogenic amplifiers; measured effective input noise temperatures in the 1 – 12 GHz range, with results as low as 2.3 K with a standard uncertainty of 0.3 K, corresponding to a noise figure of 0.034 dB ± 0.004 dB.

Jointly with the THz Bio-imaging Project, we developed and demonstrated a terahertz receiver with a quasi-optical adapter for coupling incident radiation into the receiver. The receiver is based on heterodyne detection with a hot-electron-bolometer (HEB) mixer. A cryocooler was procured and instrumented for housing the receiver portion of the radiometer.

3.3 Nano-scale high-frequency on-wafer probing

The emerging requirements for on-wafer probing at the nano-scale are clearly being driven by the ever-decreasing scale of microelectronic devices, as defined by Moore's law, and current research directed toward basic manipulation of individual atoms and molecules for constructing new electronic devices. The ever-increasing demands for bandwidth and speed of information transfer also impacts nano-technology. Smaller and faster means that nano-electronics devices must be able to operate at ever-higher frequencies, and developments and advances in the microwave, semiconductor, computing, and magnetic and electric data-storage industries will not be possible without the ability to perform reliable and accurate high-frequency on-wafer measurements at nano-scale resolutions, and high impedances.

Technical Strategy: Develop and characterize new probing technologies based upon high-frequency scanned-probe microscopy and micro-electromechanical systems (MEMS) with sub-micrometer resolution. The goal of the project is to develop metrology for quantitative imaging and measurement of electromagnetic field components and the characterization of nanoscale electrical and magnetic devices, and materials by establishing accurate spatially resolved time and frequency-domain on-wafer measurements.

Technical Accomplishments: We will summarize progress on several aspects of this program:

RF-Scanning Probe Microscope (SPM): We have developed a universal microwave SPM probe station. The head is replaceable and the system can work as RF-STM, AFM, near field scanning probe or as a high impedance non contact probe with nanometer spatial positioning. We developed calibration procedures to characterize the properties of RF-STM, AFM heads with the sensor (MEMS, STM tip, etc.) up to 50 gigahertz. The head response enables us to measure the true signals at the tip of the non-contact probes and to assess the invasiveness of the probes measuring the voltage and current at the given position on the wafer.

Calorimetric Probe Development: Previous generations of bimaterial, calorimetric MEMS probes displayed unwanted curling, resulting in a low yield of functional probes per wafer. To solve the problem and increase their yield per wafer we designed a SiN/SiO/SiN three-layer cantilever. The design was first modeled to assure the required sensitivity. The cantilevers were fabricated in the NIST clean room and found to be in good agreement with the models. They showed significant increase in yield per wafer, and possessed the required thermal sensitivity for microwave power imaging [5].

Measurement of RF Field Component: We demonstrated the capability of the developed calorimetric probes for measurement of high-frequency electromagnetic field components.

High-frequency Characterization of Carbon Nanotubes (CNT): We have demonstrated that calibrated on-wafer measurements can be used to characterize the broadband frequency response of high-impedance devices such as multi-walled CNTs.

Measurement of Magneto-mechanical Ratio: Within our MEMS program we developed a MEMS-based approach to the measurement of the magneto-mechanical ratio g' through the Einstein-de Hass effect. Knowledge of g' is important for understanding of magnetization dynamics, which is critical for the development and optimization of materials for spin electronics and magnetic data storage. The extraction of material properties from microwave measurements is critically dependent on proper understanding of the underlying physics of the magnetization dynamics. An independent estimate of the g-factor is highly desirable because it would fix one of the important fitting parameters for these measurements. The Einstein-de Haas measurement of g' is one way to obtain the g-factor independently. This effect it is based on the resonant mechanical response of a magnetic thin-film to an external excitation [6].

3.4 Advances in antenna measurements

NIST currently maintains near-field antenna measurement standards and capabilities for frequencies from 1.5 to 60 gigahertz as described earlier. The recent integration of a dynamic laser tracker system provides accurate information on probe position errors of our mechanical scanners. This implementation now enables us to carry out full scanning-probe position error corrections using the position-error-correction theory and algorithms we developed several years ago to correct for the difference between the ideal scanning lattice and the imperfect lattice resulting from mechanical errors. These corrections further reduce the uncertainty of the NIST pattern calibrations, and become more significant as frequencies increase.

We have extended the frequency range of our antenna measurement capability with two new facilities, developed over recent years. A new smaller extrapolation range, on an optical table, provides on-axis gain measurement capability for small antennas from 50 to 110 GHZ [7]. A more complete characterization and the inclusion of polarization measurement capability are necessary before we offer customer calibrations using this system. We anticipate these 50 to 110 GHz gain and polarization services will be available in the next year.

Capabilities on the second, smaller planar near-field scanning facility have also been recently extended. NIST can now perform near-field antenna pattern measurements for small/medium aperture antennas from 1.5 to 110 GHz using this facility. In addition to these enhancements, we are performing an internal comparison on all three of the NIST near-field range types (planar, cylindrical, spherical) to verify performance and refine uncertainties. Our capability with all three types of ranges is unique.

4. CONCLUSIONS

This paper summarizes the present state of high-frequency metrololgy programs at NIST that focus on providing measurement traceability. The Electromagnetics Division has other programs focused applied research and special measurement problems. We are actively assessing the impact of our legacy calibration programs against the emerging needs of new technologies, and this paper should be viewed in that context. We firmly believe that fundamental changes in technology and economics may also change the ways that we establish measurement traceability in the future.

ACKNOWLEDGEMENTS

Many people contributed to the programs described herein – see the NIST website for details.

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