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National Institute of Standards and Technology

Technology Administration

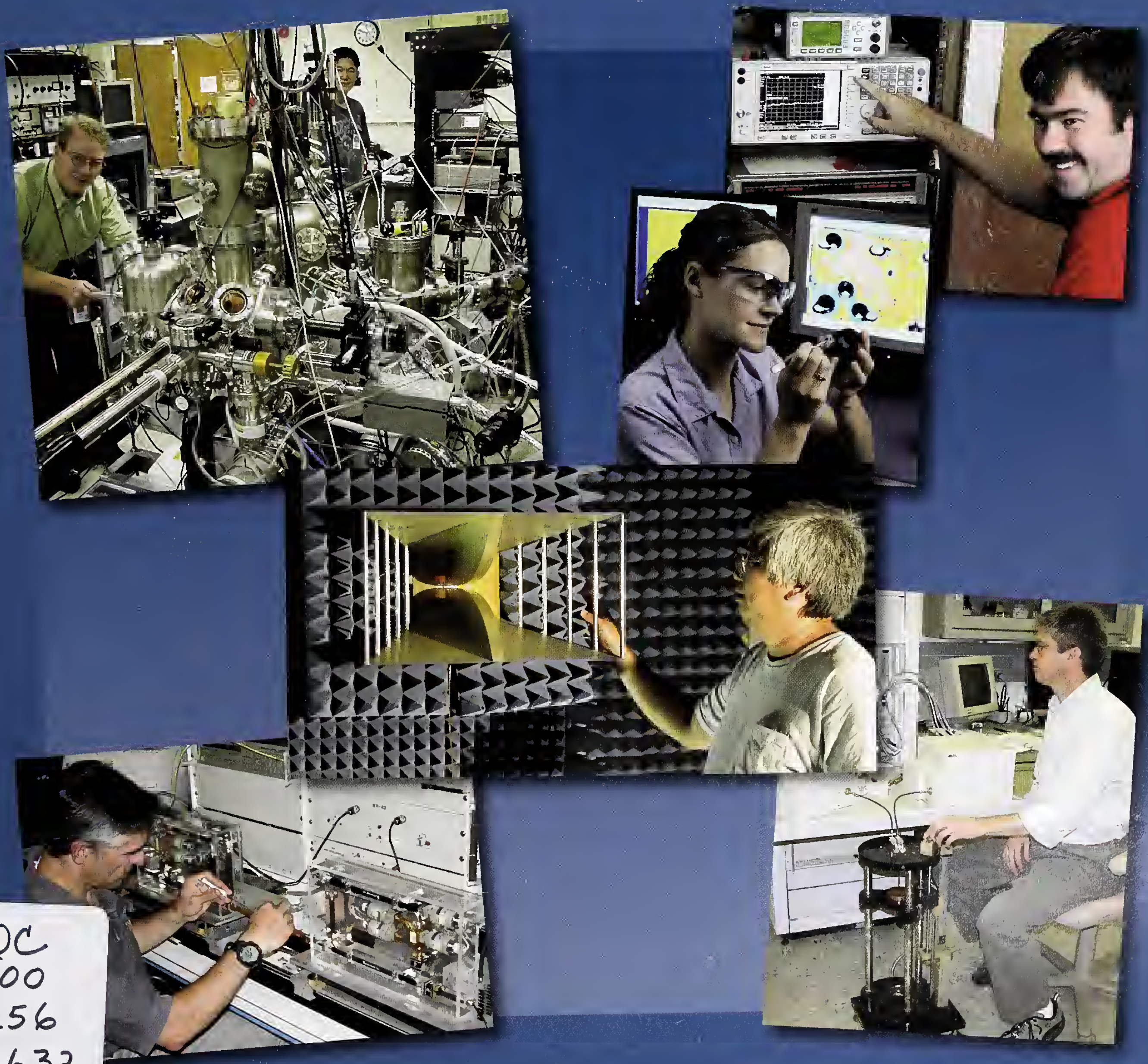
U.S. Department of Commerce

NISTIR 6632

January 2005

Electromagnetics Division

Programs, Activities, and Accomplishments



The Electronics and Electrical Engineering Laboratory

One of NIST's seven Measurement and Standards Laboratories, EEEL conducts research, provides measurement services, and helps set standards in support of: the fundamental electronic technologies of semiconductors, magnetics, and superconductors; information and communications technologies, such as fiber optics, photonics, microwaves, electronic displays, and electronics manufacturing supply chain collaboration; forensics and security measurement instrumentation; fundamental and practical physical standards and measurement services for electrical quantities; maintaining the quality and integrity of electrical power systems; and the development of nanoscale and microelectromechanical devices. EEEL provides support to law enforcement, corrections, and criminal justice agencies, including homeland security.

EEEL consists of four programmatic divisions and two matrix-managed offices:

Semiconductor Electronics Division

Optoelectronics Division

Quantum Electrical Metrology Division

Electromagnetics Division

Office of Microelectronics Programs

Office of Law Enforcement Standards

This document describes the technical programs of the Electromagnetics Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, Telephone: (301) 975-2220, On the Web: www.eeel.nist.gov

On the cover (clockwise from upper left): Rob Owings and Seongshik Oh, Elizabeth Mirowski (© 2004 Geoffrey Wheeler), John Ladbury, Bill Riddle, Doug Tamura, Ron Ginley.

Electronics and Electrical Engineering Laboratory

Electromagnetics Division

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U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
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Contents

Welcome

The Electromagnetics Division is a critical national resource for a wide range of customers. U.S. industry is the primary customer both for the division's measurement services and for technical support on the test and measurement methodology necessary for research, product development, manufacturing, and international trade. The division represents the U.S. in international measurement intercomparisons and standards development related to radio-frequency and microwave technology, electromagnetic fields, and superconductors. The division also provides measurement services and expert technical support to other agencies of the federal government to support its programs in domestic and international commerce, national defense, transportation and communication, public health and safety, and law enforcement.

The division is organized into three groups. The groups' projects are led by senior technical staff with the assistance of physicists, engineers, technicians, and research associates, as well as graduate and undergraduate students.

The **Radio-Frequency Electronics Group** conducts theoretical and experimental research to develop basic metrology, special measurement techniques, and measurement standards necessary for advancing both conventional and microcircuit guided-wave technologies; for characterizing active and passive devices and networks; and for providing measurement services for power, noise, impedance, material properties, and other basic quantities.

The **Radio-Frequency Fields Group** conducts theoretical and experimental research necessary for the accurate measurement of free-space electromagnetic field quantities; for characterization of antennas, probes and antenna systems; for development of effective methods for electromagnetic compatibility assessment; for measurement of radar cross section and radiated noise; and for providing measurement services for essential parameters.

The **Magnetics Group** develops measurement technology for industries broadly concerned with magnetic information storage and superconductor power, spanning the range from practical engineering to theoretical modeling. The group disseminates the results of its research through publications in refereed journals, presentations at conferences and workshops, and participation in standards organizations.

A separate Division program is forging new directions for the advancement of wireless technology via the development of standards for a new generation of broadband wireless access products.

We hope that this collection of information will help you in understanding the work of the division and in making use of the technical capabilities and services that we provide for industry, government, and academia. We invite you to visit our Web site, http://www.boulder.nist.gov/div818. This site will provide you with more information on our projects and measurement-related software, and reprints of our publications. Thank you for your interest in the Electromagnetics Division.

Dennis Friday, Chief, Electromagnetics Division

Michael Kelley, Leader, Radio-Frequency Electronics Group

Perry Wilson, Leader, Radio-Frequency Fields Group

Ron Goldfarb, Leader, Magnetics Group

Introduction to Technical Programs

The division carries out a broad range of technical programs focused on the precise realization and measurement of physical quantities throughout the radio spectrum. Key directions include: (a) the development of artifact reference standards, services and processes with which industry can maintain internationally recognized measurement traceability; (b) the advancement of technology through the development of new measurement techniques that are theoretically and experimentally sound as well as relevant and practical; (c) the assessment of total measurement uncertainties; and (d) the provision of expert technical support for national and international standards activities. We strive to perform leading-edge, high-quality research in metrology that is responsive to national needs. Division programs cover the following technical areas:

Fundamental Microwave Quantities

The fundamental microwave quantities program develops standards and methods for measuring impedance, scattering parameters, attenuation, power, voltage, and thermal noise, and provides essential measurement services to the nation.

New Directions in Microwave Electronics

New thrusts in microwave metrology include the characterization of nonlinear properties of devices, the linear and nonlinear characterization of wireless systems, precise on-wafer measurement of ultra-high-speed waveforms, and methods for contact and noncontact electrical probing of nanoscale electronic structures.

Electromagnetic Properties of Materials

The electromagnetic properties of materials program develops theory and methods for measuring the dielectric and magnetic properties of bulk and thin-film materials throughout the radio spectrum.

Antennas and Antenna Systems

The antennas and antenna systems program develops theory and techniques for measuring the gain, pattern, and polarization of advanced antennas; for measuring the gain and noise of large antenna systems; and for analyzing radar cross-section measurement systems.

Electromagnetic Compatibility

The electromagnetic compatibility program develops theory and methods for measuring electromagnetic field quantities and for characterizing the emissions and susceptibility of electronic devices and systems, in both the frequency and time domains.

Magnetodynamics and Spin Electronics

The program in magnetodynamics and spin electronics undertakes experimental research on fundamental aspects of magnetization switching, precession, and damping at the nanoscale for applications in magnetic information storage (such as magnetoresistive read heads, recording media, and magnetic random access memory) and magnetic devices (such as oscillators driven by the transfer of quantum-mechanical electron spin angular momentum to magnetic films).

Magnetic Sensors and Scanned-Probe Microscopy

The program in magnetic sensors and scanned-probe microscopy is developing new sensors and systems for the low-noise detection of extremely weak magnetic fields for imaging and measurement applications in data storage, microelectronics, medicine, and national security.

Superconductor Characterization and Standards

The program in superconductor characterization and standards develops measurement methods for the electric, magnetic, and mechanical properties of high-temperature and low-temperature superconductor wires and tapes for power applications.

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Fundamental Microwave Quantities: Power

Technical Contacts:
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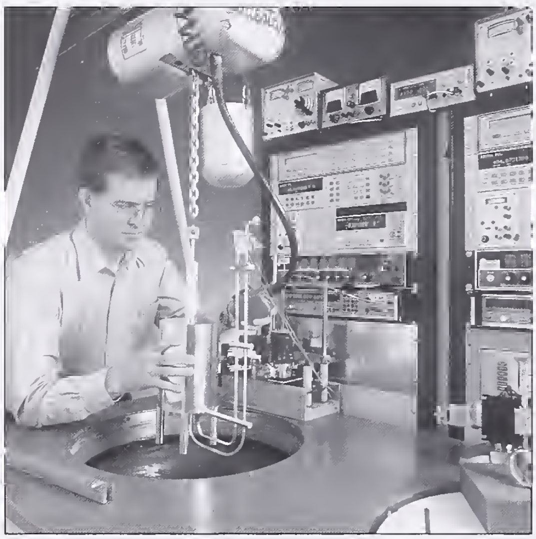
Ron Ginley

Staff-Years (FY 2004):
3 professionals
3 technicians

Goals

This project develops, maintains, and improves standards, systems, and methods for measuring power over the frequency range from 100 kilohertz to 110 gigahertz. It provides measurement services and support to U.S. industrial and government laboratories.



Jim McLean prepares to lower a waveguide microwave calorimeter into a water bath. © Geoffrey Wheeler

Customer Needs

A system's output power level is frequently the critical factor in the design, and ultimately the performance, of radio-frequency (**RF**) and microwave equipment. Accurate measurements of power and voltage allow designers and users of measuring and test equipment to determine whether performance specifications are met. Inaccurate measurements can lead to over-design of products, and hence, increased costs. Economic gains are realized through improvements in accuracy. State-of-the-art calibration services are needed so that customers can maintain quality assurance programs in the manufacture and distribution of their products. The availability of these services allows customers to be globally competitive.

Several emerging technologies have microwave power metrology needs that will require new services. High-bit-rate optoelectronics devices such as those used for the internet will need broadband characterization up to 110 gigahertz. An increasing number of applications, including some in homeland security, are using frequencies above 100 gigahertz.

Technical Strategy

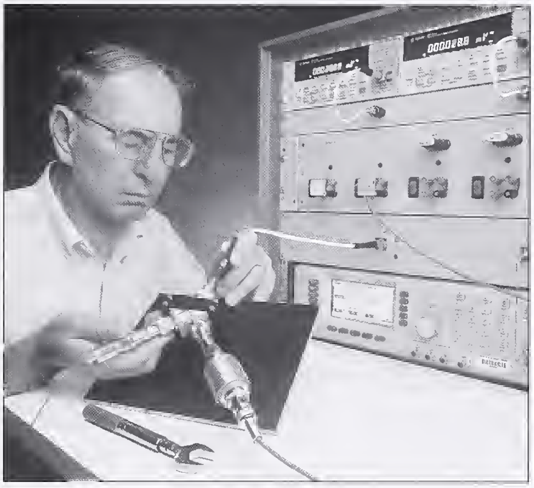
The two primary areas of current work in microwave power are improvements in measurements above 50 gigahertz and maintenance of calibration services with a wide variety of connector types. Basic research into quantum-based microwave power measurement is also being performed.

Measurements above 50 Gigahertz — For a number of years, power measurements at NIST above 50 gigahertz have been based on calorimetric and six-port measurements. NIST's internal standards were characterized in the calorimeters and the measurements transferred to customer devices by use of a six-port. The internal standards were modified commercial power sensors, and the calorimeters were designed specifically for these standards. Measurement services have been available in 1 gigahertz steps from 50 to 75 gigahertz and from 92 to 96 gigahertz. It takes about 1 day to characterize a few customer devices at each frequency.

Improvements in our standards are needed for a number of reasons. Frequency coverage in 1 gigahertz steps is not adequate for characterizing broadband devices such as optoelectronics devices that operate at 40 gigabits per second. It is also not adequate to cover new applications at frequencies above 75 gigahertz. The commercial power sensors that were originally modified to create our internal standards can no longer be obtained. Existing internal standards no longer produce reliable results in the calorimeters.

In order to address these problems, power measurement services between 50 and 110 gigahertz are being rebuilt with numerous improvements. For some applications, manually tuned Gunn diode oscillators have been replaced with backward-wave oscillators that can be electronically controlled. It is therefore, much easier to do multiple frequency measurements. A single backward-wave oscillator tube can also cover the entire frequency band from 75 to 110 gigahertz. A direct comparison system that can evaluate a customer device at about 50 frequencies per day will replace the six-port systems. The WR-15 (50 to 75 gigahertz) system has been completely evaluated, while the WR-10 (75 to 110 gigahertz) system has been constructed, but not yet evaluated. New calorimeters have been designed for both WR-10 and WR-15. They will accommodate a wider variety of internal standards than the present calorimeters. They were also designed so that a feedback system could be implemented and reduce the time required per frequency. Future plans include the extension of the direct comparison measurements to 1.85 millimeter coaxial connectors that will allow measurements from DC to 65 gigahertz with a single connector. Finally, a long-term goal is to develop a new internal standard to replace our existing standards.

The immediate beneficiary of these improvements will be the Optoelectronics Division. It has primary responsibility for characterizing high-bit-rate digital systems that are currently being developed for optical-fiber communications systems and the internet. In order to do that, they have an immediate need for broadband RF power calibration of diode detectors from DC to 65 gigahertz (preferably in 100 megahertz steps) with an eventual requirement of measurements up to 110 gigahertz.



John Juroshek measuring a coaxial power detector.
© Geoffrey Wheeler

Other customers will also benefit from these improvements. The transition from six-port to direct comparison measurements will result in a lower cost service with comparable uncertainty. Generally, coaxial systems are more useful to most customers than waveguide systems. Thus, the addition of a 1.85 millimeter coaxial connector direct comparison system will significantly help industry develop new products with these connectors. For the near future, 1.85 millimeter devices will be traceable to the WR-15 and 2.4 millimeter calorimetric primary standards.

We plan to assemble, test, and evaluate uncertainty of new WR-15 and WR-10 calorimeters. We will develop a feedback system for the new calorimeters that reduces the period of time in which the RF source must deliver power. This is important for extending the lifetime of the backward wave oscillator tubes. We will complete a direct comparison system for power detectors with 1.85 millimeter coaxial connectors.

Maintenance and Improvement of Existing Standards — We offer RF and microwave power measurement services for 5 types of coaxial connectors and 7 waveguide sizes. Short-term maintenance of these systems requires that they be continuously checked for reliability and updated as needed. The quality system defines the checks and measurements that need to be done.

We also offer voltage measurements from 30 kilohertz to 100 megahertz and a high-power (1 to 1000 watt) measurement service from 1 to 1000 megahertz. On a long-range time scale, measurement system components need to be replaced in order to maintain the quality of the system. Of particular concern in this area is that the bolometric standards with WR-15, WR-10, and 2.4 millimeter coaxial connectors cannot be replaced. We anticipate that we will have to develop our own standards in the future.

In the near future, we will deliver calibration services in power and voltage, update the quality manual, offer high power measurements at both the input and output plane of the customer's DUT, and transfer 100 kilohertz to 10 megahertz measurements to a direct-comparison system.

Quantum Based RF Power Measurement — RF power measurements have traditionally been traceable to DC power measurements. NIST's primary and transfer standards all rely on this technique in which temperature changes due to RF and DC power are measured and compared. The largest uncertainty in the measurements is due to differences in the location of the RF and DC power dissipation.

An alternative approach is to measure the field strength of microwaves through their effect on the quantum state of atoms. In this measurement, a group of atoms are prepared in a single quantum state. They are then exposed to microwaves at a frequency that corresponds to the energy difference between this state and a second quantum state. The atoms will oscillate between the two states at a frequency that is proportional to the field strength. The process is known as a Rabi oscillation. By measuring the number of atoms in each state, the field strength can be determined. A proof-of-concept experiment was conducted in collaboration with the Physics Laboratory. The next stage in this work will be an experiment that accurately compares a traditional measurement with the quantum measurement.

Accomplishments

- **Quantum-Based Microwave Power** — In collaboration with the Physics Laboratory, the RF magnetic field strength of 9.193 gigahertz microwaves in a cavity was determined by measuring the Rabi oscillation of cesium atoms passing through the cavity. The experiment used a small fountain apparatus originally designed for use as an atomic clock. The magnetic field measurement depends only on atomic parameters and the time the atoms spent in the cavity. This ties an RF measurement directly to atomic parameters. Additional measurements of the cavity properties were used to determine the microwave power incident on the cavity. This was compared with the incident power as determined through a traditional measurement. The two differed by 5 percent, which was considerably smaller than the uncertainty in the comparison.

- **Waveguide Direct Comparison** — A direct-comparison system for WR-15 and WR-10 waveguide has been constructed. The WR-15 system has been tested and its uncertainty analysis completed. This system will reduce the time required to evaluate a customer mount by a factor of about 50 from our previous six-port. It also has a slightly lower uncertainty on average.

- **New Waveguide Calorimeters** — New WR-15 and WR-10 calorimeters have been designed. These new calorimeters will replace older versions that have become unreliable. They will be able to characterize a wider variety of bolometric standards and have been designed so that feedback control can be used to reduce the time required for source operation. These improvements will make it easier to calibrate instruments at a greater number of frequencies and provide more options for transfer measurements, and should also be compatible with any future bolometric standards developed by NIST.

- **Quality Manual** — A quality system has been implemented for both calorimetric power measurements and for the transfer of those measurements to customer systems through six-port and direct comparison systems. The quality system largely documents measurement practices that have been in place for a number of years.

Calibrations

- Power and voltage calibrations were performed on 128 devices in FY 2003 and on 129 devices in FY 2004.

Short Courses

- Annual presentation at NIST/ARFTG Short Course on Microwave Measurements.

Collaborations

- Physics Laboratory, quantum-based RF power measurement.

Recent Publications

T. P. Crowley, E. A. Donley, and T. P. Heavner, "Quantum-Based Microwave Power Measurements: Proof-of-Concept Experiment," *Rev. Sci. Instrum.* **75**, 2575-2580 (August 2004).

T. P. Crowley and F. R. Clague, "A 2.4 mm Coaxial Power Standard at NIST," British Electromagnetic Conf., Harrogate, U.K. (November 2001).

J. R. Juroshek, "NIST 0.05-50 GHz Direct Comparison Power Calibration System," Conf. Precision Electromagn. Meas., Sydney, Australia, pp. 166-167 (May 2000).

Fundamental Microwave Quantities: Scattering Parameters and Impedance

Goals

This project provides traceability for microwave measurements in scattering parameters, impedance, and attenuation. It supports the microwave industry by developing standards and new measurement techniques. It develops methods for assessing and verifying the accuracy of vector network analyzers.

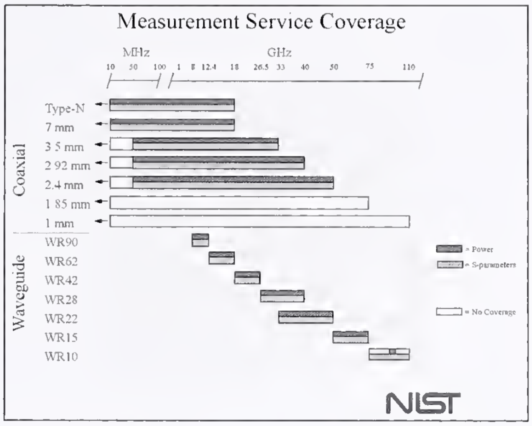
Customer Needs

Vector network analyzers (**VNAs**) are the single most important instrument in the microwave industry. These instruments are commonly found on production lines and in calibration and research laboratories. Vector network analyzers are typically calibrated daily, and the accuracy of their measurements can vary significantly after calibration, depending on the operator's skill, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost-effective techniques to monitor and verify the accuracy of VNA measurements. In addition, industry requires validation of techniques and procedures they develop. We support these needs by providing consultations on measurement techniques and uncertainty characterization. We also offer an extensive array of measurement services that allow VNA users to establish and gain confidence in their own capabilities.

Technical Strategy

There is an increasing demand for scattering-parameter (*s*-parameter) measurements. This is particularly evident for measurements above 50 gigahertz. The demand is coming from many emerging technologies including high-bit-rate digital systems and other communication systems. Support for higher frequencies and new connector types is needed. At the same time, the demand for existing measurement services is also increasing. We are developing improved *s*-parameter calibration services and techniques to support industry needs. The principal areas of our efforts include: support for existing calibration services; developing new calibration capabilities; and developing new calibration and measurement technology and techniques.

The existing calibration services cover an enormous range of connector types and frequency ranges. Both coaxial connector and waveguide devices are measured. Even though the commercial VNAs have measurement capabilities and uncertainties similar to those that NIST has, there is still a very strong



NIST s-parameter and power measurement services

demand for the classical artifact-based type of measurement to support the very large installed base of legacy equipment. We support this demand with device-based measurement services. Additionally, the existing *s*-parameter services are necessary to support the mismatch correction for power calibrations. Verification of measurement systems and calibrations is one of our most important tasks, and we will continue to improve our check-standard capabilities through an improved database and operator interface.

International comparisons play an important part in validating *s*-parameter measurements at NIST. These comparisons help us ensure that our *s*-parameter capabilities are comparable to those of other national metrology institutes. This relationship insures that users of the NIST calibration services will be able to compete in the international market. We will continue to participate in as many international comparisons as is practical.

Another service we provide to help customers have confidence in their measurements is the NIST Measurement Comparison Program. This program allows a customer to measure a set of devices previously characterized by NIST, and then compare their results to NIST's along with the identification of NIST's uncertainties. This program will be broadened to include new connector types and additional capabilities.

New services are being developed to address the increased demand from the optical-fiber communication industry, wireless systems, and aerospace, military and general communications industries, to name a few. Higher frequencies and smaller connector sizes are being used on a routine basis. We

Technical Contact:
Ron Ginley

Staff-Years (FY 2004):
2 professionals
4 technicians

are meeting some of these needs by adding the 1.85 millimeter and the 1.0 millimeter connector size capabilities to our measurement services in the next year. We are also looking at support requirements for other connector types including the 7/16 connector and 75-ohm-based connectors.

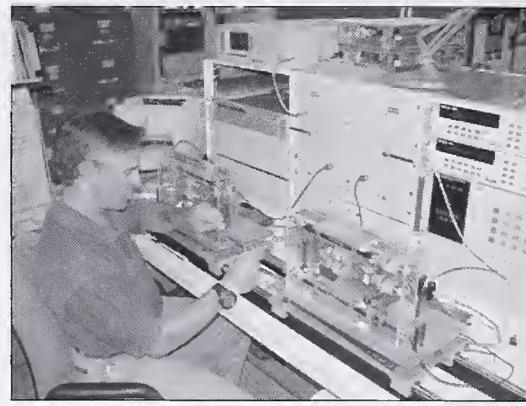
There is a general agreement among the principal users and makers of VNA systems that there is still much to be understood about VNA calibrations and measurements. We are taking a very active role in developing VNA calibration and measurement theory and techniques. We have developed the theory and techniques for correcting lower accuracy Open-Short-Load calibrations to almost the accuracy of the line-reflect-line (**LRL**) calibrations (regarded as the most accurate) for one-port measurements. We will be pursuing a similar correction process for two-port measurements. Because of the parity between customer capabilities and those at NIST, we are looking at different ways to support VNA systems in industry. Verification of VNA calibrations is very important; the current verification process is not as good as it needs to be. We have developed a program that will compare the contents on verification disks to measurements made based on LRL calibrations, and then we will write new verification disks based on the LRL measurements and uncertainties. We currently have the capability for only a few of the verification disk formats; we will expand these capabilities and support new formats for VNA systems that are just becoming available.

We will continue to provide *s*-parameter measurements to industry, establish 1.85 millimeter *s*-parameter calibration service, establish 1.85 millimeter and 1.0 millimeter NIST Measurement Comparison Program Kits, provide software and techniques to support the DOD's use of commercial VNAs, add capabilities for the Agilent 8753 and PNA series VNAs to the verification disk program, finish development of the Web-based check standard database for *s*-parameter and power measurements, and investigate methods to enhance two-port calibrations on VNAs.

Accomplishments

- The 30 megahertz Precision Attenuation Measurement System was transferred to the U.S. Army Primary Standards Laboratory. The transferred system replaced older equipment at the Army.

- We delivered an updated System 3 Dual Six-Port System (18 to 40 gigahertz) to the Navy Primary Standards Laboratory. This system will help support critical, high-frequency waveguide measurements made by the Navy.



Calibrating the WR-42 six-port system

- We developed and delivered a suite of VNA software to the Air Force Primary Standards Laboratory. This software included programs to calibrate commercial VNAs, take measurements from the VNAs, read and write corrected verification disks, read and compare calibration disk's data, and one-port calibration correction routines. The Air Force estimates that the use of these packages will save them in excess of $100 000 a year.

- A quality system has been implemented for *s*-parameter measurements.

Calibrations

- The *s*-parameter and impedance measurement services were performed on 124 devices in FY 2003 and on 203 devices in FY 2004.

Short Courses

- Annual presentation at NIST/ARFTG Short Course on Microwave Measurements

Collaborations

Optoelectronics Division, oscilloscope and power head calibrations

Committee Participation

- ARFTG Executive Committee; NCSLI Measurement Comparison Program Committee, NCSLI Intrinsic and Derived Standards Committee, and NCSLI U.S. National Measurement Requirements Committee.

Recent Publication

J. R. Juroshek, "Correcting for Systematic Errors in One-Port Calibration Standards," 62nd ARFTG Conf. (December 2003).

Fundamental Microwave Quantities: Noise

Technical Contact:
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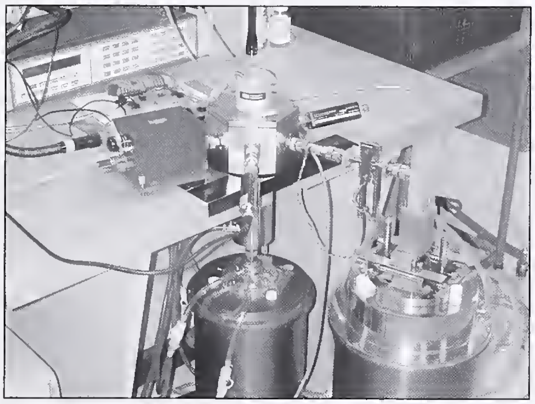
Staff-Years (FY 2004):
2.5 professionals
1.5 technicians
1 research associate

Goals

This project develops methods for very accurate measurements of thermal noise and provides support for such measurements in the communications and electronics industries and in other government agencies.



Amplifier noise-parameter measurements using two cryogenic standards, one to calibrate the radiometer and one for input to the amplifier.

Customer Needs

Noise is a crucial consideration in designing or assessing the performance of virtually any electronic device or system that involves detection or processing of a signal. This includes communications systems, such as cellular phones and home entertainment systems, as well as systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and millimeter-wave devices in these areas is huge and will grow larger. Important trends requiring support include the utilization of higher frequencies, the growing importance of low-noise amplifiers and transistors, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters requested by industry are the noise temperature of a one-port source and the noise figure of an amplifier.

Noise power is also the quantity that is measured in passive remote sensing, such as that used to measure properties of the earth's surface from satellites or airplanes. The growing importance of such measurements for climate monitoring, weather forecasting, agriculture, and other applications has highlighted the need for better calibration techniques, smaller uncertainties, and compatibility between results from different instruments.

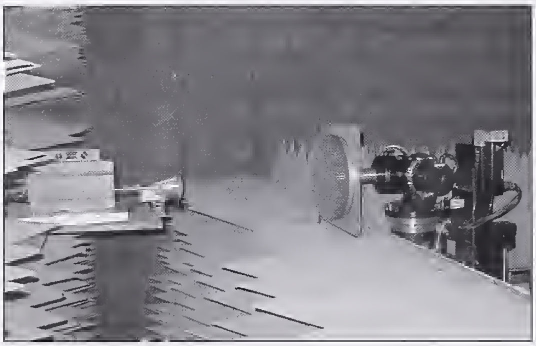
Technical Strategy

We are working in three general areas: traditional noise-temperature measurements, characterization of amplifier and transistor noise properties, and calibration of remote-sensing radiometers. In traditional noise-temperature measurements, we offer measurement services at 30 and 60 megahertz and from 1 to 40 gigahertz for coaxial sources, and from 8.2 gigahertz to 65 gigahertz for waveguide sources. Recent improvements have reduced the time required for these measurements, thereby reducing the costs to our customers.

The second general thrust of the project is in amplifier and transistor noise-parameter measurements. The long-term goals in this area are to improve techniques for measurement of noise parameters of low-noise amplifiers and transistors, to develop measurement capability for noise parameters of amplifiers with coaxial connectors from 1 to 12 gigahertz, and to provide a mechanism for industry to access this capability, either through measurement comparisons or a measurement service.

A new thrust of the project is in improving methods for calibration and validation of microwave radiometers used for remote sensing from satellite or airplane. The central element of this effort will be the development of microwave brightness-temperature standards, comprising both standard radiometers and standard calibration targets. The standard radiometers will be used to measure customer calibration targets at NIST, and the standard calibration targets will be used in measurements at outside facilities, as well as for comparison measurements with the NIST standard radiometer.

Our goals for this coming year are to measure the noise parameters of a low-noise amplifier for an interlaboratory comparison with NPL, measure the noise parameters of a cryogenic amplifier belonging to the Terahertz Project, and measure noise parameters of ultra-large-scale integration (ULSI) devices on wafer for comparison to IBM and RFMD. We intend to study the uncertainties in on-wafer measurements of noise parameters; design a temperature-controlled, shielded, anechoic chamber for standard radiometer(s); use the Physics Laboratory's infrared (**IR**) imaging system to study thermal gradients in a calibration target used for microwave remote sensing; and continue to provide noise-temperature measurement services.



Calibration target being tested in anechoic chamber.

Accomplishments

- **Amplifier Noise-Parameter Measurements and Verification** — The Noise Project completed development of a measurement capability for noise parameters of low-noise amplifiers (**LNAs**), including a Monte Carlo assessment of uncertainties. We also completed and successfully implemented two types of verification tests for such measurements. All tests were satisfied within the uncertainties, thereby providing support for both the measurement results and the associated uncertainty estimates.

- **Variable-Termination Unit** — A variable-termination unit (**VTU**) was designed, fabricated, and tested. The VTU will be used in noise-parameter measurements, allowing automated switching to an array of different input terminations for the amplifier, rather than the manual disconnecting and connecting that is currently used.

- **Traceability for Microwave Remote-Sensing Measurements** — A plan was developed for establishing traceability to NIST for microwave remote-sensing measurements. The plan includes the theory necessary to link microwave remote-sensing measurements to primary noise standards. It was documented in a NIST internal report and in a conference paper.

- **Measurement of Microwave Brightness Temperature** — Preliminary measurements were performed on a hot calibration target borrowed from the NOAA Environmental Technology Laboratory. A standard gain horn (**SGH**) was characterized by the Antenna Metrology Project and was connected to the measurement plane of the Noise Project's WR-42 waveguide radiometer to form a standard radiometer for remote sensing. This standard radiometer was then set up to view the calibration target mounted in the anechoic chamber. The target's brightness temperature was measured for different distances and compared to the nominal brightness temperature based on the sampled physical temperature. Satisfactory to good agreement was obtained, and possible areas of improvement were identified.

- **Target Reflectivity** — A study performed in FY 2004 on the effects of target reflectivity in the calibration of microwave remote-sensing radiometers was documented in a conference paper and a journal paper. This study found that a common approximation used in calibrating microwave radiometers leads to errors that can be quite significant.

- **Detector Linearity Study** — Measurements were made on tunnel diode detectors of the type typically used in microwave remote-sensing radiometers. These measurements included variations in detector temperature as well as output load impedance. Results point to improved test methods and a way to greatly reduce the cost associated with radiometer linearity tests.

- **CEOS Definitions** — The Web site for standard definitions was maintained (http://www.boulder.nist.gov/div813/stdterms/index.htm) and Chapters 1 and 2 of the compilation of standard definitions for microwave radiometry were accepted by the Committee on Earth Observation Satellites (**CEOS**).

Calibrations

- In FY 2004, calibrated 8 devices for customers.

Collaborations

- Warsaw University of Technology (W. Wiatr), on-wafer noise-parameter measurements

- IBM and RFMicroDevices (Kelvin Project), noise parameters of ULSI devices

- National Polar-orbiting Operational Environmental Satellite System (**NPOESS**), ATMS Calibration and Validation Working Group

- NOAA Environmental Technology Laboratory (A. Gasiewski and M. Klein), calibration target characterization

- NASA Microwave Instrument Technology Branch (P. Racette, J. Piepmeier), calibration target characterization

- Physics Laboratory (J. Rice, C. Johnson), radiometer calibration and validation and target characterization

- Information Technology Laboratory (K. Coakley, J. Splett), nonlinear modeling of tunnel diode detectors

Standards and Technical Committee Participation

- Consultative Committee on Electricity and Magnetism (**CCEM**), Working Group on Radio Frequencies, Chairman

- IEEE Microwave Theory and Techniques Society, Technical Committee on Microwave Low-Noise Techniques, TC-14

- IEEE Geoscience and Remote Sensing Society Technical Committee on Instrumentation and Future Technologies

- IEEE Geoscience and Remote Sensing Society liaison to IEEE Standards Board

- CEOS Working Group on Calibration and Validation, Microwave Sensors Subgroup, Standard Terminology compilation (Chapters I and II)

Recent Publications

J. Randa, D. K. Walker, A. E. Cox, and R. L. Billinger, "Errors Resulting from the Reflectivity of Calibration Targets," *IEEE. Trans. Geosci. Remote Sensing,* in press.

J. Randa, A. E. Cox, D. K. Walker, M. Francis, J. Guerrieri, and K. MacReynolds, "Standard Radiometers and Targets for Microwave Remote Sensing," Int. Geoscience and Remote Sensing Symp. (IGARSS), Anchorage, AK, paper 2TU_30_10 (September 2004).

D. K. Walker, K. J. Coakley, and J. D. Splett, "Nonlinear Modeling of Tunnel Diode Detectors," Int. Geoscience and Remote Sensing Symp. (IGARSS), Anchorage, AK, paper 81TH_14_11 (September 2004).

J. Randa, D. K. Walker, A. E. Cox, and R. L. Billinger, "Errors Due to the Reflectivity of Calibration Targets," Int. Geoscience and Remote Sensing Symp. (IGARSS), Anchorage, AK, paper 4TH_70_02 (September 2004).

J. Randa, D. K. Walker, M. Francis, and K. MacReynolds, "Linking Microwave Remote-Sensing Measurements to Fundamental Noise Standards," Conf. Precision Electromagn. Meas., London, U.K., pp. 465-466 (June 2004).

G. Free, J. Randa, and R. L. Billinger, "Radiometric Measurements of a Near-Ambient, Variable-Temperature Noise Standard," Conf. Precision Electromagnetic Meas., London, U.K., pp. 414-415 (June 2004).

W. Wiatr and D. K. Walker, "Systematic Errors in Noise Parameter Determination Due to Imperfect Source Impedance Measurement," Conf. Precision Electromagnetic Meas., London, U.K., pp. 416-417 (June 2004).

J. Randa and D. K. Walker, "Amplifier Noise-Parameter Measurement Checks and Verification," 63rd ARFTG Conf., Fort Worth, TX, pp. 41-45 (June 2004).

J. Randa, "Traceability for Microwave Remote-Sensing Radiometry," NIST Interagency Report, NISTIR 6631 (June 2004).

New Directions in Microwave Electronics: Nonlinear Device Characterization

Technical Contacts:
Don DeGroot
Jeffrey Jargon

Staff-Years (FY 2004):
2 professionals
1 research associate

"Your work represents an important development in this area, opening a new application of ANNs to measurement standards."

Prof. Zhang, Nortel/NSERC Industrial Chair in CAE Carleton University January 2002

Goals

This project develops new and general measurement methods for characterizing nonlinear microwave and millimeter-wave circuits, semiconductor devices, and advance technology elements. It refines and transfers these methods to research and development laboratories through international collaborations.

Jeffrey Jargon measures a commercial harmonic phase reference standard using the large-signal network analyzer.

Customer Needs

Radio-frequency (**RF**) measurements from tens of megahertz to hundreds of gigahertz are used extensively throughout the development and deployment of advanced technology. Historically the focus was on linear network characterization, but more recently the commercial wireless industry identified the need for new methods in nonlinear network analysis and requested NIST's assistance. Additionally, a growing effort in advanced bio- and nano-technologies is now calling for related nonlinear system identification tools.

The needs in nonlinear RF network analyzers are two-fold. Engineers and researchers require accurate measurements of the absolute wave variables of periodic, harmonically rich signals, not just the wave-variable ratios at single frequencies that are used in linear network analysis. Second, they need efficient methods of capturing the observed wave variables over an adequate range of states in order to model the behavior of their nonlinear networks. We formed the Nonlinear Device Characterization (**NDC**) Project in FY97 to address these specific needs, working first with the commercial wireless world.

Technical Strategy

The main strategy of the NDC Project is to develop accurate measurements of broadband wave-variables (up to 50 gigahertz at this point, with plans to expand). With solid measurement techniques and statements of measurement uncertainty we can pursue our secondary strategies of new measurement-based modeling and canonical nonlinear devices for measurement verification. While we often demonstrate the application of new methods in industrial problems, our strong physical foundation naturally leads to methods and tools that are general and support a wide range of advanced technology.

The NDC Project established a new and unique measurement facility by acquiring a passive intermodulation (**PIM**) analyzer and prototype large-signal network analyzer (**LSNA**). The facility provides a unique collection of equipment and methods in open U.S. research laboratories, and the most general approach to measuring large-signal responses in nonlinear RF networks. We are developing accurate calibration and measurement techniques for users of LSNA-like equipment, and recently collaborated with the Vrije Universiteit Brussel on new statistical approaches for vector network analyzer identification and correction. We are also developing a nonlinear superconducting device for the verification of wave-variable phase, and have developed a diode circuit-verification wafer for an interlaboratory measurement comparison.

One way the NDC Project is supporting high-frequency radio design is in measurement-based modeling, that is, linking the accuracy of a model to the quality measurements. Industrial experts estimate that the "basic" RF power amplifier accounts for over 50 percent of base station costs and over 20 percent of the total wireless link cost, due to high development costs. These amplifier circuits are supposed to be linear, but this is often an unrealistic specification in commercial applications, where cost and battery drain margins are small. More accurate nonlinear device and amplifier models would reduce radio transceiver costs dramatically. Likewise, the cost of microwave transistor mixer circuits could be reduced. Through various collaborations, the NDC team has developed artificial neural-network models for power amplifiers, and extracted mixer transfer admittance models, both from LSNA measurements. Additional contributions in this area will significantly improve design-cycle efficiency and trade between manufacturers.

The NDC team is now working on methods that will bring wave-variable measurements to nanotechnology development. An emerging project strategy is to focus on connection methods and new calibration frameworks to extend our expertise in broadband wave-variable measurements to the electrical characterization of nanostructures.

Next year we will develop behavioral modeling methods for power amplifiers using large-signal network analyzer data. We will formulate large-signal scattering parameter descriptions of nonlinear circuits under specific stimuli. We will develop stochastic methods of vector network analyzer identification and correction. We will do an uncertainty analysis of LSNA wave-variable measurements. We will participate in an interlaboratory measurement comparison for LSNAs and LSNA-like equipment.

Accomplishments

- **Improved Calibration of Large-Signal and Traditional RF Vector Network Analyzers Using New Maximum Likelihood Estimator** — In collaboration with the Vrije Universiteit Brussel, a statistical method was developed for identifying vector network analyzer parameters, and the uncertainty in the parameters. This is a new framework to LSNA and VNA measurement correction, and deviates significantly from traditional deterministic methods used in the industry.

- **Discovered Warm-Up Drift in Harmonic Phase Reference Standards Used in Commercial Large-Signal Network Analyzers** — In collaboration with Information Technology Laboratory an empirical model was developed for the warm-up drift in harmonic phase standards used to calibrate the phase distortion of nonlinear vector network analyzers. Using this model, we prescribed a stability point. This contribution significantly improves LSNA phase distortion calibrations, and is already being adopted by LSNA users.

- **Completed Development of Relationships between Nonlinear Large-Signal Scattering Parameters and Nonlinear Large-Signal Impedance Parameters** — We provided the industrial community with important new figures of merit for nonlinear microwave circuit analysis that can be readily employed as computer-aided tools for wireless component design or in measurement comparison experiments.

- **Demonstrated Nonlinear Superconductor Device as Potential Phase Reference** — A high-temperature superconducting device with a calculable nonlinear response was developed. Measured third-order response on LSNA and showed its phase match prediction. This device is potentially the first true, independent standard in verifying LSNA phase calibrations.

Collaborations

- Vrije Universiteit Brussel, Department ELEC, Statistical LSNA identification and correction techniques.

- University of Florence, Electrical and Computer Engineering Department, Measurement-based behavioral models of microwave mixer circuits.

- Information Technology Laboratory, Harmonic Phase Reference repeatability and drift analysis; Wave-variable and scattering parameter statistics; Interlaboratory measurement comparison data analysis.

- University of Colorado, Boulder, Artificial Neural Network modeling of nonlinear amplifier circuits and VNA calibration standards.

Awards

- Department of Commerce Silver Medal for NDC Project, 2003
- Automatic RF Techniques Group (**ARFTG**) Conference Best Poster Paper

Professional Committee Participation

- Jeff Jargon serves as Chair of the IEEE MTT-S Technical Committee on Microwave Measurements
- Jeff Jargon serves as Chair of the IEEE MTT-S Standards Coordinating Committee

Recent Publications

J. A. Jargon, J. D. Splett, D. F. Vecchia, and D. C. DeGroot, "Modeling Warm-Up Drift in Commercial Harmonic Phase Standards," Conf. Precision Electromagn. Meas., pp. 612-613 (July 2004).

J. A. Jargon, K. C. Gupta, and D. C. DeGroot, "Nonlinear Large-Signal Scattering Parameters: Theory and Application," 63rd ARFTG Conf., pp. 157-174 (June 2004).

"Thank you for the paper [Multiline TRL Revealed]. Comprehensive and useful!"

Marek Schmidt
Philips Semiconductor
April 2003

D. C. DeGroot, Y. Rolain, R. Pintelon, and J. Schoukens, "Corrections for Nonlinear Vector Network Analyzer Measurements Using a Stochastic Multi-Line/Reflect Method," IEEE MTT-S Int. Microwave Symp., pp. 1735-1738 (June 2004).

J. Jargon, K. C. Gupta, A. Cidronali, and D. DeGroot, "Expanding Definitions of Gain by Taking Harmonic Content into Account," *Int. J. RF Microwave Computer-Aided Eng.* **13**, 357-369 (September 2003).

J. A. Jargon, D. C. DeGroot, and D. F. Vecchia, "Repeatability Study of Commercial Harmonic Phase Standards Measured by a Nonlinear Vector Network Analyzer," 62nd ARFTG Conf., pp. 243-258 (December 2003) (best poster paper award).

A. Cidronali, G. Loglio, J. A. Jargon, K. A. Remley, I. Magrini, D. C. DeGroot, D. Schreurs, K. C. Gupta, and G. Manes, "RF and IF Mixer Optimum Matching Impedances Extracted by Large-Signal Vectorial Measurements," Proc. European Gallium Arsenide and Other Compound Semiconductor Application Symp, (October 2003).

J. C. Booth, K. Leong, S. A. Schima, J. A. Jargon, and D. C. DeGroot, "Design and Characterization of a Superconducting Nonlinear Reference Device," 62nd ARFTG Conf., pp. 61-70 (December 2003).

D. Schreurs, J. A. Jargon, K. A. Remley, D. C. DeGroot, and K. C. Gupta, "Artificial Neural Network Model for HEMTs Constructed from Large-Signal Time-Domain Measurements," 59th ARFTG Conf., pp. 31-36 (June 2002).

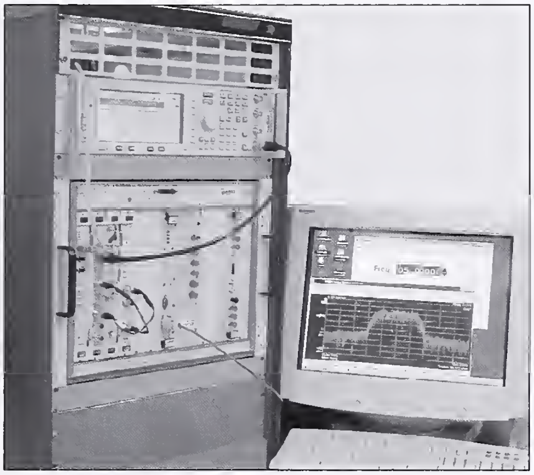
D. C. DeGroot, J. A. Jargon, and R. B. Marks, "Multiline TRL Revealed," 60th ARFTG Conf., pp. 131-155 (December 2002).

J. A. Jargon, K. C. Gupta, and D. C. DeGroot, "Applications of Artificial Neural Networks to RF and Microwave Measurements," *Int. J. RF Microwave Computer-Aided Eng.* **12**, 3-24 (January 2002).

New Directions in Microwave Electronics: Metrology for Wireless Systems

Goals

The Metrology for Wireless Systems project develops improved measurement methods for both well-established and newly emerging wireless communication systems in response to pressing needs of U.S. industry and the public safety sector. This goal is achieved by use of advanced measurement technology to (1) develop new and improved calibrations for existing instrumentation, (2) accurately represent the effects of nonlinear elements such as power amplifiers on system performance, and (3) implement cost-effective methods for reliable radio communications for the public safety sector.



Instrumentation that aids in the refinement and development of metrology for wireless communication systems.

Customer Needs

Wireless communication systems take many shapes and forms, including cellular technology for voice, image, and video transmission, high-speed local-area and ad-hoc data networks, and RFID tags for applications such as toll payment and inventory control. The first responder community utilizes wireless telecommunications extensively in emergency scenarios, as well as for broadband data transmission for maps, photos, and other images. Accurate system characterization is essential in all of these applications because it increases efficiency of system design and validates overall system performance. For the commercial sector, this leads to increased productivity and revenue. For the public safety sector, accurate system characterization can mean the difference between life and death in emergency situations.

Technical Strategy

The commercial wireless market and the first responder community have similar yet distinct needs. As a result, this project is divided into two main thrusts: Measurements for Wireless Systems and Improved Communications for First Responders.

Measurements for Wireless Systems — This project was newly formed in FY 2004, having originated in the Nonlinear Device Characterization project in FY 2000. The project takes advantage of new measurement instrumentation capable of accurately characterizing systems that have nonlinear elements to develop new and refined calibration and measurement methods appropriate for next-generation and broadband wireless system technologies. Using this instrumentation we are able to evaluate measurements made on equipment commonly utilized in the industry.

Our goals include development of impedance mismatch correction techniques for vector signal generators in their large-signal operating state, development and characterization of test and calibration signals useful to the wireless industry, and assessment of the effect of standard test equipment nonidealities on system characterization.

Improved Wireless Communications for First Responders — Until now, first responders have had little guidance in predicting how well their systems will operate in a variety of difficult transmission scenarios. We are developing test methods to characterize signal degradation, including attenuation and phase distortion, in complex environments including large buildings and basements.

In particular, we are focusing on development of wideband measurement methods in the new 4.9 gigahertz public safety radio band for transmission of voice, data, images, and video. The project is also involved in compilation of an array of straightforward, inexpensive, retrofitable techniques to be used in emergency weak-signal scenarios, such as tunnels, basements, and collapsed buildings.

Technical Contact:
Kate Remley

Staff-Years (FY 2004):
2 professionals
3 research associates

"Wireless applications have quickly grown to become an important driver for semiconductor products and technologies."

The International Technology Roadmap for Semiconductors: Executive Summary (2003)

Project staff and others from the Electromagnetics Division carry out propagation measurements (using the mobile cart behind the staff) and investigate methods for weak-signal detection at a large public building scheduled for implosion in New Orleans.

"Inadequate and unreliable wireless communications have been issues plaguing public safety organizations for decades. In many cases, agencies cannot perform their mission-critical duties"

"Statement of Requirements: Background on Public Safety Wireless Communications," The SAFECOM Program, Department of Homeland Security, v. 1.0 (March 10, 2004)

Accomplishments

- **Mathematical Description of Third-Order Intermodulation Products** — We developed a straightforward, device-independent mathematical description of third-order intermodulation distortion in amplifier circuits based on two-tone analysis. We verified the description with measurements on the large-signal network analyzer (**LSNA**). The measurements included a technique that extends the modulation bandwidth of the LSNA. Accurate characterization of intermodulation is a key step in the field of pre-distortion correction, where the nonlinear behavior of a system is measured in real time and the incoming signal is distorted to compensate for the system's nonlinearity.

- **Method to Measure the Small-Signal Reflection Coefficient of Vector Signal Generators under Large-Signal Operating Conditions** — This technique consists of a one-port measurement performed at the output port of a vector signal generator while it is in its large-signal operating state. The method captures both the standard and the phase-conjugated mixing behavior associated with nonlinear devices. This new method uses the unique capabilities of the LSNA to overcome limitations on VNA measurements of reflection coefficient, and will enable mismatch correction of sources in their operating state, including their phase-conjugated behavior, for the first time.

- **Comparative Measurements of Multisine Test and Calibration Signals** — This collaboration involves measurements of identical multisine signals with instrumentation capable of characterizing nonlinear systems, including an LSNA, a vector signal analyzer, a calibrated sampling oscilloscope (with the Optoelectronics Division) and the NIST Sampling Waveform Analyzer (with the Quantum Electrical Metrology Division). Some of these instruments may enable development of new types of multisine calibration signals, since they either now have or will soon have uncertainty analyses associated with their measurements.

- **Calibration of a Receiver-Based Measurement System for Weak-Signal Detection** — We developed a method to measure absolute electric field strength using a communications receiver-based system. This method will enable measurement of very weak signals from public safety transceivers in terms of absolute field strength. We have already applied the method in a collaborative effort with the Phoenix Fire Department, which has conducted extensive signal testing of their radio systems in large public buildings in the Phoenix area.

- **Measurement Methods for Public Safety in the 4.9 Gigahertz Frequency Band** — We developed a normalization technique that facilitates calculation of a common digital system figure of merit called error vector magnitude (**EVM**). We developed a multisine test signal to emulate the broadband digital signal used in common transmission schemes. Public safety organizations hope to take advantage of such existing wideband transmission protocols shifted in frequency to the 4.9 gigahertz band. This work aims to provide them with a simple test protocol for their broadband channels.

- **Investigation of Metallic Debris as *Ad Hoc* Antenna Arrays** — We carried out measurements using building materials such as conduit, pipe, and rebar as radiating structures to investigate whether they can enhance signal transmission and reception from deep within a building. Using metallic debris as an ad hoc radiator in a damaged or collapsed building may provide a new type of lifesaving tool in emergency scenarios where communication is made difficult by large amounts of debris.

Collaborations

- Agilent Technologies, K.U. Leuven: device-independent mathematical description of third-order intermodulation in weakly nonlinear systems

- K.U. Leuven: method to extend measurement bandwidth of LSNA for intermodulation distortion measurements

- Georgia Tech: normalization to facilitate calculation of error vector magnitude (EVM) in broadband wireless systems

- K. U. Leuven and Georgia Tech: development of multisine signals to emulate broadband digital modulation

- Colorado School of Mines: measurement of active mixers

- Optoelectronics Division and Information Technology Laboratory: measurement application of jitter correction technique

- Optoelectronics Division and Quantum Electrical Metrology Division: measurement comparison of multisine signals from instrumentation with measurement uncertainty analyses

- Phoenix Fire Department: measurements of signal strength during field experiments on signal quality in large public buildings

Awards

- Department of Commerce Silver Medal for Nonlinear Device Characterization Project Participation, 2003

- ARFTG Conference Best Paper Award, 2003

Professional Committee Participation

- IEEE International Microwave Symposium Technical Program Subcommittee 7 on Nonlinear Circuit Analysis and System Simulation

- Automatic RF Techniques Group (**ARFTG**) Nonlinear Vector Network Analyzer Users' Forum, coordinator

Recent Publications

K. A. Remley, D. F. Williams, D. Schreurs, and J. Wood, "Simplifying and Interpreting Two-Tone Measurements," *IEEE Trans. Microwave Theory Tech.,* in press.

J. Verspecht, D. F. Williams, D. Schreurs, K. A. Remley, and M. D. McKinley, "Linearization of Large-Signal Scattering Functions," *IEEE Trans. Microwave Theory Tech.,* in press.

D. F. Williams, F. Ndagijimana, K. A. Remley, J. Dunsmore, and S. Hubert, "Scattering Parameter Models and Representations of Microwave Mixers," *IEEE Trans. Microwave Theory Tech.,* in press.

D. Schreurs, K. A. Remley, W. Van Moer, "NVNA Users' Forums: Mission and Overview," Proc. 2004 European Microwave Conf., in press.

K. A. Remley, D. Schreurs, D. F. Williams, and J. Wood, "Extended NVNA Bandwidth for Long-Term Memory Measurements," IEEE MTT-S Int. Microwave Symp., pp. 1739-1742 (June 2004).

D. Schreurs, K.A. Remley, and D.F. Williams, "A Metric for Assessing the Degree of Device Nonlinearity and Improving Experimental Design," IEEE MTT-S Int. Microwave Symp., pp. 795-798 (June 2004).

D. Schreurs, K.A. Remley, M. Myslinksi, and R. Vandermissen, "State-Space Modeling of Slow-Memory Effects based on Multisine Vector Measurements," 62nd ARFTG Conf., pp. 81-88 (December 2003).

D. Schreurs, M. Myslinski, and K. A. Remley, "RF Behavioural Modelling from Multisine Measurements: Influence of Excitation Type," Proc. 2003 European Microwave Conf., pp. 1011-1014 (October 2003).

New Directions in Microwave Electronics: High-Speed Microelectronics

Technical Contact:
Dylan Williams

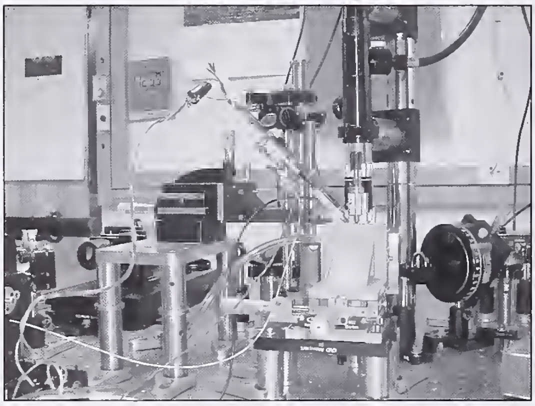
Staff-Years (FY 2004):
1 professional
1 technician
1 research associate

"A major roadblock will be the need for high frequency, high pin count probes and test sockets; research and development is urgently required to enable cost-effective [test] solutions with reduced parasitic impedance."

2003 International Technology Roadmap for Semiconductors

Goals

This project supports the microwave, telecommunications, computing, and emerging nanoelectronics industries through research and development of high-frequency on-wafer electrical metrology for micrometer-scale and nanoscale electrical devices. It is developing electrical metrology in coaxial transmission lines to 110 gigahertz and on-wafer metrology to 400 gigahertz for microwave signal and signal source characterization, wireless systems, high-speed microprocessors, and high-speed nanocircuits and interconnects, and the telecommunications industry. The work is interdisciplinary and relies on strong collaborative efforts with the Optoelectronics Division.



The NIST electro-optic sampling system provides traceability for our measurements and calibrations. Developed jointly with the Optoelectronics Division.

Customer Needs

The rapid advance in the speed of modern telecommunications and computing systems drives this project. Characterizing signal integrity in microprocessors requires at least 10 gigahertz of calibrated measurement bandwidth on structures fabricated on a nanoscale. Limited available bandwidth is pushing wireless systems into the millimeter-wave region of 30 to 100 gigahertz, where accurate microwave signal and signal source characterization is difficult. Optical links operating at 40 gigabits per second require electrical metrology to 110 gigahertz. Emerging high-speed digital circuits with clock rates of over 100 gigahertz require electrical metrology to 400 gigahertz. These extraordinary advances in technology require new high-speed coaxial and on-wafer microwave signal and waveform measurements. Because the speed of the devices is often linked to size, it is important to develop this high-speed metrology at both conventional IC and nanoscale dimensions and at both conventional and high impedances.

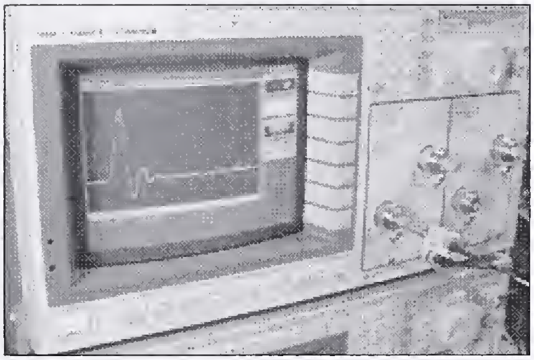
Technical Strategy

Coaxial connectors pose insurmountable economic hurdles for high-speed telecommunications and computing. For example, a single coaxial adapter that supports frequencies to 110 gigahertz costs upwards of $1000. This project focuses on the only feasible alternative: high-speed on-wafer metrology. The project's initial focus on developing metrology for on-wafer network analysis for MMICs has been expanded to include metrology for silicon ICs and differential interconnects. More recently the project has further expanded the focus to noninvasive probing on a nanoscale and to ultra-high-speed modulated microwave signal, signal-source, and waveform characterization.

The project focuses on extending fundamental microwave and on-wafer metrology to higher frequencies and to modulated signals and waveforms. Working together with EEEL's Optoelectronics Division, we have developed a fully calibrated electro-optic sampling system for characterizing photodetectors and calibrating oscilloscopes for microwave signal characterization. This has set the foundation for a number of new developments in microwave metrology, including: modulated microwave signal and coaxial signal-source characterization to 110 gigahertz, verifying the 3-mixer calibration, and performing electro-optic on-wafer scattering and waveform measurements beyond 110 gigahertz. This fundamental metrology tool will be crucial to bringing a new generation of calibrated high-frequency oscilloscopes, MTAs, and related instruments to the microwave engineer's workbench.

Whenever possible, we are extending the use of these instruments directly to the wafer level. We are not only developing calibration procedures for today's high-performance electrical probes, but we are also laying the foundations for 200 gigahertz to 400 gigahertz calibrations for tomorrow's probes. We are also developing techniques for performing noninvasive high-impedance on-wafer waveform measurements for signal-integrity characterization in digital silicon ICs and other small circuits. This effort is particularly important for the development of electrical metrology for nanoscale devices, which, due to their small sizes, have extremely high electrical impedances.

Our plan is to electrically characterize an active high-impedance probe with our existing VNA calibration methods. We will then characterize the same probe on our 200-gigahertz-bandwidth EOS system. This will lay the groundwork for very-high-speed on-wafer calibrations for digital IC and nanoelectronics. We will develop joint time-domain/frequency-domain uncertainty analysis for coaxial photodiode pulse sources. The calibration and uncertainty representation will include imperfections in the electro-optic sampling system and electrical mismatch corrections, and will be suitable for calibrating oscilloscopes with coaxial ports in either the time or frequency domains to 110 gigahertz. We will develop pulse sources with 400 gigahertz bandwidth. Based on these sources, develop on-wafer waveform characterization ability to 400 gigahertz. We will apply high-speed waveform metrology to microwave problems, including the characterization of electrical phase standards, microwave sources, and microwave mixers.



Traceable mismatch-corrected 50 gigahertz microwave oscilloscope calibration with an EOS-characterized photodetector.

Accomplishments

- **High-Impedance Probe Characterization** — We developed a frequency-domain method of characterizing high-impedance probes suitable for performing noninvasive on-wafer waveform and signal-integrity measurements.

- **Electro-Optic Sampling System** — In a collaborative effort with the Optoelectronics Division, we built an on-wafer electro-optic sampling system. We have developed calibration methods and uncertainty analyses in coaxial media to 110 gigahertz and on-wafer to 200 gigahertz.

- **On-Wafer Measurement and Characteristic Impedance** — We developed accurate multiline TRL on-wafer calibrations, on-wafer calibration verification methods, and compact calibration alternatives with verified accuracy. We developed an accurate method of measuring the characteristic impedance of a transmission line fabricated on lossy silicon substrates and an accurate on-wafer calibration using this method.

- **Multiport and Coupled-Line Characterization** — We developed instrumentation and methods for accurately and completely characterizing multiports and small printed coupled lines.

- **Thin-Film Characterization** — In collaboration with our Microwave Materials Group, we characterized low-*k* dielectrics fabricated at SEMATECH using transmission-line methods developed at NIST.

Software

- Time-Base-Correction Software for jitter and time-base-distortion correction of oscilloscope measurements.

- StatistiCAL measurement software implementing general on-wafer and coaxial calibrations with orthogonal distance regression and uncertainty estimation.

- MultiCal measurement software implementing the multiline TRL calibration.

- Four-port measurement software for performing orthogonal two-port, three-port, and four-port measurement with in-line calibrations and inexpensive hardware.

- Software for characteristic impedance of silicon transmission lines designed to accurately determine the characteristic impedance of transmission lines fabricated on silicon substrates.

- CausalCat Software: For computing causal characteristic-impedance magnitude from the phase of the integral of the Poynting vector over the guide cross section.

Recent Publications

D. F. Williams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Calibrated 200 GHz Waveform Measurement," *IEEE Trans. Microwave Theory Tech.*, in press.

J. Verspecht, D. F. Williams, D. Schreurs, K. A. Remley, and M. D. McKinley, "Linearization of Large-Signal Scattering Functions," *IEEE Trans. Microwave Theory Tech.*, in press.

D. F. Williams, F. Ndagijimana, K. A. Remley, J. Dunsmore, and S. Hubert, "Scattering-Parameter Models and Representations for Microwave Mixers," *IEEE Trans. Microwave Theory Tech.*, in press.

P. Kabos, H. C. Reader, U. Arz, and D. F. Williams, "Calibrated Waveform Measurement with High-Impedance Probes," *IEEE Trans. Microwave Theory Tech.* **51**, 530-535 (February 2003).

D. F. Williams, C. M. Wang, and U. Arz, "An Optimal Multiline TRL Calibration Algorithm," Int. Microwave Symp., pp. 1819-1822 (June 2003).

K. A. Remley, D. F. Williams, D. Schreurs, G. Loglio, and A. Cidronali, "Phase Detrending for Measured Multisine Signals," 61st ARFTG Microwave Measurement Conf., pp. 73-83 (June 2003) (ARFTG best paper award).

K. A. Remley and D. F. Williams, "Sampling Oscilloscope Models and Calibrations," Int. Microwave Symp. (invited), pp. 1507-1510 (June 2003).

A. Louh, U. Arz, H. Grabinski, D. F. Williams, D. K. Walker, and A. Weisshaar, "Broadband Impedance Parameters of Asymmetric Coupled CMOS Interconnects: New Closed-Form Expressions and Comparison with Measurements," 7th IEEE Workshop on Signal Propagation on Interconnects, Siena, Italy (May 2003).

U. Arz, P. Kabos, and D. F. Williams, "Measuring the Invasiveness of High-Impedance Probes," 7th IEEE Workshop on Signal Propagation on Interconnects, Siena, Italy (May 2003).

P. D. Hale and D. F. Williams, "Calibrated Measurement of Optoelectronic Frequency Response," *IEEE Trans. Microwave Theory Tech.* **51**, 1422-1429 (April 2003) (EEEL 2003 Outstanding Authorship Award).

New Directions in Microwave Electronics: Radio-Frequency Nanoelectronics

Goals

This project develops fundamental metrology, instrumentation techniques, and theory needed for the microwave, telecommunications, magnetic recording, and computing industries. Research is focused on standards and tools for visualization and characterization of materials and devices at the nanoscale. Emphasis is on waveform and frequency-domain metrology of nanoscale interconnects and packaging, and on microscopy and imaging of devices and materials.

Customer Needs

The National Nanotechnology Initiative calls for the creation of a new research and development infrastructure to tackle the challenges and opportunities of nanotechnology. Full exploitation of the potential of nanotechnology requires long-term interdisciplinary research across such fields as chemistry, physics, materials science, electronics, biotechnology, medicine, and engineering. Research will be conducted to provide fundamental measurements needed for future generations of hardware needed to replace semiconductor and magnetic technology in a decade or so. Our expertise in microwave metrology, optics, materials characterization, clean room microfabrication — as well as collaboration with other projects — helps us develop new tools and materials characterization techniques for nanotechnology in the frequency range up to 100 gigahertz and beyond.

Technical Strategy

Based on an understanding of the physics of the interaction between materials and electromagnetic waves, we are focusing on the development of new experimental tools and techniques that address future needs of industry that require noninvasive probing and characterization of submicrometer and nanoscale structures at radio frequencies (**RF**). We are working with the Magnetics Group, the Optoelectronics Division, and the Materials Science and Engineering Laboratory to apply on-wafer measurement methods to nanoscale devices and interconnects such as carbon nanotubes or Si nanowires. We are developing techniques for performing noninvasive on-wafer waveform measurements for signal-integrity characterization in digital silicon integrated circuits and in magnetic recording media, and calibration procedures for nanoscale electrical and magnetic probing systems. In order to characterize nanostructures, it is important to extend the high spatial and temporal resolution of existing nanoprobes. The objective is to observe and control the dynamical evolution of physical phenomena in nanostructures. The development of nanometer-scale RF pump-probe techniques, nanometer-scale feedback and control, and other probes of local behavior are sought to provide new insight into nanoscale phenomena.

Radio-Frequency Atomic-Force Microscope (RF-AFM) Development — Several projects require high-frequency, near-field imaging capabilities. We are developing experimental techniques in collaboration with the Magnetics Group and the Materials Science and Engineering Laboratory for measuring the high-frequency response and noise of small magnetic structures. The focus is on the contribution of the edges on the measured characteristics of small samples. The results from different experimental techniques will be compared and evaluated to get a better understanding of the behavior of small magnetic elements.

The possibility of chip-to-chip wireless communication requires the design of novel micrometer-scale antennas with special radiation patterns to ensure the errorless transfer of data from chip to chip at high data-transfer rates. The imaging of the near-field radiation patterns of such structures is of crucial importance for such applications.

Electromagnetic compatibility (**EMC**) applications require noncontact measurements of the electromagnetic fields in the vicinity of the chip-to-wafer wiring structures. Similar requirements apply to tracing the spurious coupling channels in high-frequency devices.

To achieve the necessary sensitivity and spatial resolution for above mentioned and similar applications, some modifications to the control hardware and software of our RF-AFM microscope will be necessary. We will enhance the capabilities of our microscope to achieve the necessary performance through digital signal processor (**DSP**) control with development of the supporting software. The available scanning capabilities are well within the requirements. The control system will be designed to allow flexibility for simple future modifications that will be necessary for new applications.

Technical Contact:
Pavel Kabos

Staff-Years (FY 2004):
1 professional
1 research associate
1 graduate student

This year, we plan to design the DSP hardware for RF-AFM control and develop the necessary software. In following years, we will collaborate on the design of antennas and measure the antenna patterns for chip-to chip communication applications, characterize the eigenmodes of small magnetic structures, and relate the measured mode structure to the noise response of the devices.

Radio-Frequency Probe Development — In order to improve on the spatial resolution and spectral bandwidth of the probes for high-frequency near-field metrology applications we are also focusing on development of special probes. These probes will be designed and tailored to particular applications. This tailoring includes the spatial resolution, bandwidth, and adjustment of the design. We may implement small particles or more complex nanoscale structures on the tip area of cantilevers based on micro-electromechanical systems (MEMS). Depending on the application, these structures can be magnetic, dielectric, or more complicated composite structures that would allow either high-frequency or optical detection of the near electric and magnetic fields. We plan to characterize new MEMS-based sensors for the developed near-field imaging applications.

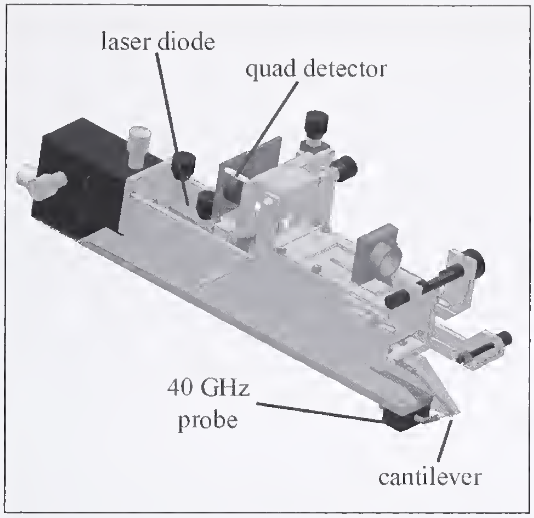
Evanescent Microwave Probe — We are participating in a collaboration with the Electromagnetic Properties of Materials project on the development of metrology for micrometer and submicrometer characterization of materials for electronic and packaging applications. We have developed new theory and software to characterize the microscopic fields in evanescent probe metrology. We will extend new software and theory for the evanescent microscope methods and do on-wafer measurements of substrate materials.

Nanomaterials and Metamaterials Characterization — Carbon nanotubes and Si-based nanowires are considered as possible option for the next generations of interconnects and high-integration-density structures. Although extensive research is ongoing on the structural, mechanical, and optical properties and applications of these materials, very little is known about their behavior in another important frequency range, from a few megahertz to 100 gigahertz and beyond. This could be due to difficulties in separating the characteristics of the investigated nanostructures from environmental influence at these frequencies. We are developing non-invasive metrology based on well developed on-wafer techniques that allow separating the behavior of the nanostructures of interest from that of their environment.

In recent years there has been increased interest in the development of composite and artificially structured materials with properties that differ significantly from the properties of standard materials. Among those are the band-gap materials for different frequency ranges and the so-called "negative index" materials that support the propagation of electromagnetic waves with opposite phase and group velocities. Due to their special properties, several challenges in the theory, tailored material design, and metrology will have to be mastered. We are working on all aspects of this challenge. In the area of metrology, we are developing techniques to measure the group and phase velocities. In the area of theory, we work on understanding the electromagnetic boundary conditions and the scattering problems that are relevant for the optimal design of these materials for particular applications. These applications may include the design of novel reference materials for broadband, high-frequency calibrations. We will characterize and measure metamaterials in collaboration with the Electromagnetic Properties of Materials project and the Complex Fields project.

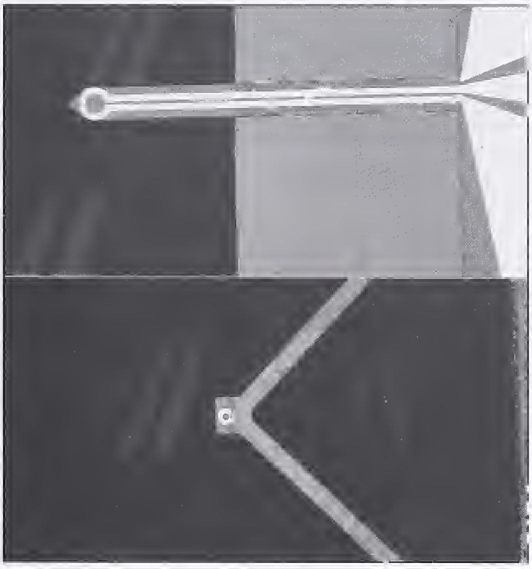
Accomplishments

- **RF-AFM Development** — In collaboration with the Nanoprobe Imaging Project in the Magnetics Group we developed a microwave AFM probe station designed to test the frequency response of high-frequency sensors. This year the RF-AFM head was redesigned (see figure). The head is attached to a standard microwave probe station furnished with a piezoelectric positioner. The head can work both as an AFM system and as a high-impedance noncontact probe with nanometer spatial positioning. The design allows positioning the probe between standard microwave on-wafer probes at a 500 micrometer separation. This requirement was necessary to be able to access standard on-wafer thru-reflect-line (**TRL**) calibration test structures. A commercial 50 gigahertz probe is attached to the *x-y-z* positioner to be able to attach the microwave probe to the MEMS waveguide structure (at the position of the cantilever in the figure). We developed calibration procedures to characterize the properties of the attached microwave MEMS structures up to 50 gigahertz. A knowledge of the MEMS sensor characteristics provides the opportunity to measure the true signals at the tip of the noncontact MEMS probe and also to assess the invasiveness of the probes used to measure the voltage and current at the given node or position on a wafer.



RF atomic force microscope head.

■ **RF Probe Development** — In collaboration with the Nanoprobe Imaging Project, we are developing several types of micromachined standard or bi-material cantilever probes with either thin-film FMR or thin-film metallic sensors to probe microwave fields near active devices. The first picture shows a loop probe for direct magnetic field detection and the second figure shows the probe for calorimetric detection of microwave magnetic fields. Similar sensors are available for electric field detection. These sensors are designed for use with the above-described RF-AFM system. The sensors can be of broad bandwidth or can be designed to be frequency selective. Absorption of the microwave energy in a Ni-Fe sensor, for example, is maximized when the microwave frequency matches the ferromagnetic resonance condition. This condition can be adjusted by changing the DC magnetic bias field, making the sensor frequency selective. On the other hand the nonmagnetic metal ring eddy-current sensor in the figure is broadband. The choice depends on the application.



MEMS sensors for detection of microwave magnetic field component. Top image is a loop sensor with a coplanar waveguide feed. The cantilever is a silicon nitride 1 micrometer thick beam. The bottom image is a bi-material sensor for calorimetric microwave magnetic field detection.

■ **Evanescent Microwave Probe** — A new theoretical model has been developed for wire evanescent microwave probes suspended over a multiple-dielectric (thin-film on dielectric substrate) test structure for performing on-chip permittivity measurements. The theory represents a significant advance in the near-field probing of materials because it can be easily extended to thin-film and multilayer structures.

■ **Local and Macroscopic Fields in Materials** — In collaboration with Electromagnetic Properties of Materials project we have developed, from basic statistical-mechanics principles, the microscopic and macroscopic relationships for the local and macroscopic fields in materials, and then related these to exact expressions for the constitutive parameters.

■ **Nanomaterial and Metamaterial Characterization** — With the Electromagnetic Properties of Materials project, the Complex Fields project, and the Magnetics Group, we developed and performed measurements on a novel metamaterial. The material consists of yttrium garnet spheres in Styrofoam. The permeability of the spheres is tuned using a DC bias magnetic field until "left-handed" behavior is observed. We plan to further develop and measure left-handed meta-, magnetoelectric, and photonic band-gap materials.

Award

■ NIST Bronze Medal for development of Pulsed Inductive Microwave Magnetometer, 2004 (Tom Silva, Tony Kos, and Pavel Kabos).

Recent Publications

P. Kabos, U. Arz, and D. F. Williams, "Multiport Investigation of Coupling of High Impedance Probes," *IEEE Microwave Wireless Comp. Lett.*, in press.

T. M. Wallis, J. Moreland, B. F. Riddle, and P. Kabos, "Microwave Power Imaging with Ferromagnetic Calorimeter Probes on Bimaterial Cantilevers," *J. Magn. Magn. Mater.*, in press.

J. Baker-Jarvis, P. Kabos, and C. L. Holloway, "Nonequilibrium Electromagnetics: Local and Macroscopic Fields and Constitutive Relationships," *Phys Rev E* **70**, 036615/1-13 (September 2004).

J. Baker-Jarvis and P. Kabos, "Modified de Broglie Approach Applied to the Schrödinger and Klien-Gordon Equations," *Phys. Rev. A* **68**, 042110/1-8 (October 2003).

C. L. Holloway, E. F. Kuester, J. Baker-Jarvis, and P. Kabos, "A Double Negative (DNG) Composite Medium Composed of Magnetodielectric Spherical Particles Embedded in Matrix," *IEEE Trans. Ant. Prop.* **51**, 2596-2602 (October 2003).

P. Kabos, H. C. Reader, U. Arz, and D. F. Williams, "Calibrated Waveform Measurement with High-Impedance Probes," *IEEE Trans. Microwave Theory Tech.* **51**, 530-535 (February 2003).

A. B. Kos, T. J. Silva, and P. Kabos, "Pulsed Inductive Microwave Magnetometer," *Rev. Sci. Instrum.* **73**, 3563-3569 (October 2002).

R. G. Geyer, P. Kabos, and J. R. Baker-Jarvis, "Dielectric Sleeve Resonator Techniques for Variable-Temperature Microwave Characterization of Ferroelectric Materials," IEEE MTT-S Int. Microwave Symp., Seattle, WA, pp. 1657-1660 (June 2002).

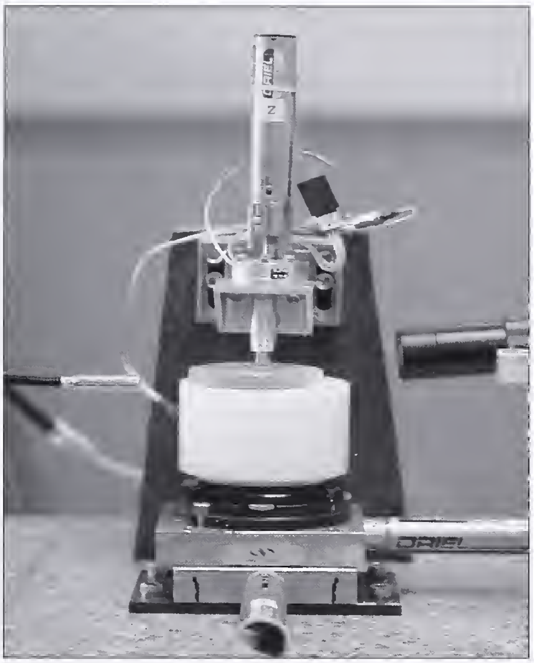
Electromagnetic Properties of Materials

Technical Contact:
Jim Baker-Jarvis

Staff-Years (FY 2004):
6 professionals

Goals

This project develops, improves, and analyzes measurement methods, uncertainties, and theory for the characterization of the complex permittivity and permeability of naturally occurring and artificial materials in the radio-frequency, microwave, and millimeter-wave spectrum as a function of temperature and bias fields. Emphasis is on metrology, thin films, liquids, biological materials, high frequencies, small scales, and artificial materials.



High-frequency evanescent microwave probe.

Customer Needs

Trends in microwave materials are toward higher frequencies, variable temperatures, and nanoscale dimensions. Currently, thin films, artificial and biological materials, substrates, and liquids are perceived as the most important measurement areas. Substrate-based components employing thin films form the basis for microelectronic circuitry. Electronic substrate materials are used in printed wiring boards (**PWB**), low-temperature cofired ceramics (**LTCC**), CPU chips, and microwave components. Industry requires new measurement methods with well-characterized uncertainties, at microwave and millimeter frequencies and over variable temperatures. Data on temperature-dependent dielectric and loss properties of ceramics, substrates, and crystals at microwave and millimeter frequencies is crucial in the wireless and time-standards arena. For example, computer-based design methods require very accurate data on the dielectric and magnetic properties of these materials over wide ranges of frequency and temperature. An understanding of loss mechanisms in low-loss crystals is important when interpreting measurement results. Artificial dielectrics are becoming commonplace and can be designed to obtain properties not exhibited in nature. New dielectric metrology is needed for these areas.

Various applications require composite dielectrics that emulate the human body's electrical properties for testing metal detectors and analyzing electromagnetic interference (**EMI**) to implanted medical devices. Measurements of liquid permittivity are needed to support biotechnology research. To support the evolving microelectronics industry, methods for characterizing nanoscale and metamaterial properties will be necessary for the development of novel new technologies. On-chip microscale-to-nanoscale measurements of permittivity are important for the microelectronics industry. Both solid and liquid dielectric reference materials are needed to provide measurement traceability to NIST. Measurement intercomparisons provide assessments of the quality of material characterization.

Newly developed thin-film materials such as high-temperature superconductors, ferroelectrics, and magnetoelectrics hold great potential for improved functionality in microwave devices, but are still in the critical stage of material development. Accurate characterization of the microwave properties of these emerging materials at this stage can have a large impact on the development of future electronic systems. Such materials can provide novel device concepts useful to the commercial, military, and metrological communities.

Technical Strategy

The project's main thrusts in 2005 are to develop measurement methods to support the health care industries, measure materials at higher frequencies, broaden our measurement temperature range, and measure advanced materials over smaller dimensions. The current specific areas of research are thin films and printed wiring boards, applications to biotechnology, low-loss dielectric and magnetic crystals, probing methods for micro-nanoscale permittivity, dielectric metrology of advanced materials such as metamaterials, superconductors, and ferroelectrics, and theoretical modeling of dielectric relaxation.

In response to needs in the microelectronics industry, we are developing accurate methods for measuring the dielectric properties of thin films using both transmission-line and resonator methods. Using a previously developed on-wafer transmission-line model, we will extend measurements of thin films to frequencies above 40 gigahertz, and will also develop a new resonator method. We will also aid the PWB and LTCC industries in measuring the permittivity of substrates at high frequencies. To this end, we will further enhance our wideband, variable-temperature metrology. We will extend the capability of our Fabry-Perot measurement system to include variable temperatures, and will complete the model for the split-post resonator. We will measure a wide spectrum of ceramic materials commonly used in the electronics industry as a function of temperature. We will continue to work with and support IPC Tasks Groups and the LTCC Working Group through measurement assistance.

To satisfy documented needs in the health care, biotechnology, and metal-detector industries, we will characterize materials that emulate the electrical properties of the human body. We will also develop a coaxial probe for *in-vitro* measurements in support of research on detection of breast cancer. In addition, in support of the biotechnology industry, we will improve our liquid measurement metrology and will compare our measurements with NPL's using the liquid measurement methods we have developed.

To enhance the understanding of the physics of high-frequency losses in dielectrics we will test ferroelectric and other crystals over wide temperature and frequency ranges using an in-house model for determination of permittivity. We will also compare the measured losses as functions of temperature and frequency to expressions in the solid-state literature.

To support the microelectronics industry in on-chip dielectric measurement metrology, we will develop methods for evanescent microwave probing and atomic-force microscopy.

To support basic research on advanced composite materials technologies, we will develop measurement metrology on metamaterials.

We will support the development of standards by attending and contributing to standards committee meetings.

To accurately determine the microwave properties of developing materials, we will combine existing on-wafer measurement techniques with lithographically defined device structures to characterize advanced materials such as high-temperature superconductors, ferroelectric, and magnetoelectric thin films. We are also applying these techniques to perform on-chip characterization of small samples of biological materials or fluids using integrated microfluidic channels and reservoirs. Device measurements are then accomplished by utilizing a number of specialized microwave probe stations, such as our cryogenic probe station or 110 gigahertz probe station.

Accomplishments

- We developed measurement metrology for measuring the broadband complex permittivity of liquids. The software is based on an in-house theoretical model for the open-circuited sample holder.

- A Standard Reference Material (**SRM**) for both relative permittivity and loss tangent has been completed and submitted to EEEL's Measurement Committee (**MCOM**). Cross-linked polystyrene samples were characterized in a mode-filtered circular-cylindrical cavity and will be available pending the approval of MCOM.

- In collaboration with S. Hagness of the University of Wisconsin, we have developed new measurement and calibration algorithms and a new electromagnetic theory for characterizing coaxial probes for use in breast cancer detection and therapy.

- We have developed new theory and software to characterize the microscopic fields in evanescent probe metrology. A new theoretical model has been developed for wire evanescent microwave probes suspended over a multiple-dielectric (thin-film on dielectric substrate) test structure for performing on-chip permittivity measurements.

- We developed from basic statistical mechanics the microscopic and macroscopic relationships for the local and macroscopic fields in materials and then related these to exact expressions for the constitutive parameters. This work has been published in Physical Review E.

- With assistance from our collaborators J. Krupka and R. Clarke, we modified our procedure for measuring materials in the Fabry-Perot resonator from 40 to 100 gigahertz, such that low-loss materials ($\tan \delta = 0.00001$) are measurable at 60 gigahertz.

- We developed software to complete the design of a 10 gigahertz metal cavity used in a new frequency discriminator design for improved phase noise performance. In addition, completed the construction of 4 additional cavities based on this design to be used by NIST and the sponsor. With Craig Nelson of the Physics Laboratory, we co-authored a paper describing a new method of reactive-tuning of resonant cavities for improved performance of temperature-controlled frequency discriminators.

- In anticipation of future needs, we completed the design and modeling of coupling loops for deposition on substrates, to be used at frequencies above 40 gigahertz in air-filled metallic cavities. This design was then tested and demonstrated with a numerical model using finite element methods (Maxwell), with very favorable results.

- Major progress has been achieved in our goal of developing techniques for measurements on ferroelectric materials. We have made high-accuracy permittivity measurements on potassium tantalate using our cryogenic system as functions of frequency and temperature. This material has low loss and tunability at low temperatures and may be a significant material for tunable antennas and phase shifters.

- For our OLES contract, we made measurements on many building materials. We are constructing a model concrete wall for propagation studies in collaboration with the Time-Domain Fields project. A comprehensive database has been initiated. In addition, a rebar scattering model has been developed.

- In collaboration with J. Krupka of the University of Warsaw, we used Bragg reflectors in our Fabry-Perot resonator and found that the system quality factor Q was increased from 150 000 to 250 000.

- A new standard for the IPC High-Frequency Task Group (D-24) has been submitted for editorial review.

- We published two technical notes that summarize techniques for measuring the conductivity and permeability of metals. In addition, the reports contain conductivity and permeability data for metals commonly used in the manufacture of weapons.

- We published a new theoretical model for the split-cylinder resonator that incorporates higher-order resonant modes, significantly broadening the frequency range of this method. Prior to this new model, complex permittivity measurements could be made only at a single frequency with the split-cylinder resonator.

- We performed measurements and collaborated with P. Kabos, C. Holloway and S. Russek on development of a novel metamaterial. The material consists of yttrium garnet spheres in Styrofoam. The permeability of the spheres is tuned using a DC bias magnetic field until left-handed behavior is observed. We plan to further develop and measure left-handed, meta-, magnetoelectric, and photonic-band-gap materials.

- We established an experimental platform to explore broadband microwave interactions of liquid and solution-based biological samples confined in microfluidic structures. We have fabricated individual components of this platform, and evaluated them using finite-element simulations. This work will provide a new approach to broadband permittivity measurements of fluids and biological samples, and will also allow the development of new techniques for exposing cell populations to well-characterized electromagnetic fields for microwave hyperthermia and specific absorption rate studies.

- We measured pair-breaking current density in high transition temperature superconducting thin films. One of the fundamental properties of superconductors is the critical-current density (J_c), which sets the upper bound for the current-carrying capacity of a superconductor. Our measurements of the nonlinear response of $YBa_2Cu_3O_{7-\delta}$ thin films show agreement with theoretical predictions for nonlinear response due to pair-breaking in d-wave superconductors, and our measurement system yields values for the pair-breaking current density that agree remarkably well with theoretical predictions of this quantity for YBCO. This measurement technique could provide an entirely new path to determining critical current densities in superconductors, and may yield intrinsic J_c values closer to theoretical predictions than conventional J_c measurement techniques.

- We developed a broadband technique for determining the complex permittivity of dielectric and ferroelectric thin films at variable temperatures. We have succeeded in obtaining consistent values for the complex permittivity of thin dielectric films over the broad frequency range from 100 hertz to 40 gigahertz by combining several different measurement techniques on the same patterned device structures. Measurements have been demonstrated on $SrTiO_3$ thin films at room temperature. Such broadband measurements will be applied to help quantify dispersion in ferroelectric films, and also to evaluate newly developed magnetoelectric thin films, as well as high-permittivity dielectric thin films.

- We have continued development of a novel broadband superconducting device that can limit large transient microwave signals encountered in hostile electromagnetic environments. We have measured the response of our superconducting microwave power limiter to high-voltage (50 volts), fast risetime (250 picoseconds) pulses, and demonstrated that the device is effective in limiting signals on timescales of under 1 nanosecond. We are exploring the application of this device to protect sensitive radio-frequency and microwave electronics from high-power transient signals, including ultra-wideband impulse jammers.

Our goals are to extend new measurement software and theory for the evanescent microscope technique (developed in collaboration with Pavel Kabos) and measure substrate materials on-wafer. We will complete a dielectric database for OLES/HS. We will develop software for support of *in-vitro* breast cancer tissue measurements (in collaboration with Pavel Kabos). We will complete measurements of KTO_3 ferroelectric and publish the results in a journal.

We plan to write a paper and submit for publication on the measurement of high-loss liquids from 50 megahertz to 10 gigahertz to help industry calibrate dielectric measurements on biological materials. We will characterize and measure a metamaterial for Boeing under DARPA funding (with Pavel Kabos). We will characterize reference fluids and biological samples using our broadband microfluidic measurement platform over the frequency range 100 hertz to 100 gigahertz.

To demonstrate application of a superconducting microwave power limiter to mitigate effects of broadband impulse jammers, we will obtain the pair-breaking current density of superconducting MgB_2 films using our nonlinear measurement techniques and explore effects of disorder and nonlocality on pair-breaking current density. We will demonstrate broadband permittivity measurements of ferroelectric thin films at variable temperatures using on-wafer measurement techniques.

Recent Publications

J. Baker-Jarvis, P. Kabos, and C. L. Holloway, "Nonequilibrium Electromagnetics: Local and Macroscopic Fields and Constitutive Relationships," *Phys Rev E* **70**, 036615/1-13 (September 2004).

M. D. Janezic, E. F. Kuester, and J. Baker-Jarvis, "Broadband Complex Permittivity Measurements of Dielectric Substrates using a Split-Cylinder Resonator", IEEE MTT-S Int. Microwave Symp., Fort Worth, TX, pp.1817-1820 (June 2004).

M. D. Janezic and J. Baker-Jarvis, "Relative Permeability Measurements for Metal-Detector Research," NIST Technical Note 1532 (2004).

M. D. Janezic, R. F. Kaiser, J. Baker-Jarvis, and G. Free, "DC Conductivity Measurements of Metals," NIST Technical Note 1531 (2004).

M. D. Janezic, "Dielectric Measurement Methods at Millimeter-Wave Frequencies," Proc. IMAPS Conf. Ceramic Interconnect Technology, Denver, CO, pp. 221-225 (2004).

J. C. Booth, K. T. Leong, S. Y. Lee, J. H. Lee, B. Oh, H. N. Lee, and S. H. Moon, "Nonlinear Microwave Response of MgB_2 Thin Films," *Supercond. Sci. Tech.* **16**, 1518-1522 (December 2003)

J. Baker-Jarvis and P. Kabos, "Modified de Broglie Approach Applied to the Schrödinger and Klien-Gordon Equations," *Phys. Rev. A* **68**, 042110/1-8 (October 2003).

C. L. Holloway, E. F. Kuester, J. Baker-Jarvis, and P. Kabos, "A Double Negative (DNG) Composite Medium Composed of Magnetodielectric Spherical Particles Embedded in Matrix," *IEEE Trans. Ant. Prop.* **51**, 2596-2602 (October 2003).

K. J. Coakley, J. D. Splett, M. D. Janezic, and R. F. Kaiser, "Estimation of Q-factors and Resonant Frequencies," *IEEE Trans. Microwave Theory Tech.* **51**, 862-868 (March 2003).

M. D. Janezic, D. F. Williams, V. Blaschke, A. Karamcheti, and C. S. Chang, "Permittivity Characterization of Low-*k* Thin Films from Transmission-Line Measurements," *IEEE Trans. Microwave Theory Tech.* **51**, 132-136 (January 2003).

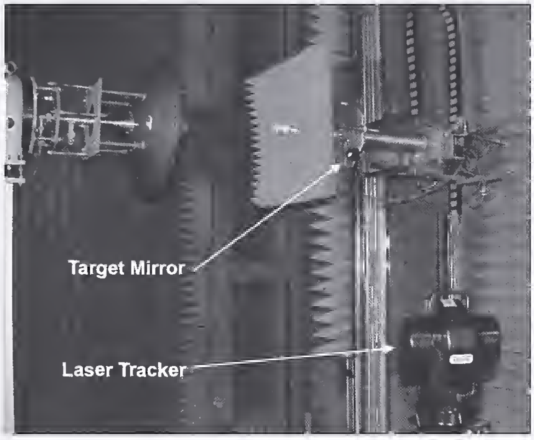
Antennas and Antenna Systems: Antenna Theory and Applications

Technical Contact:
Mike Francis

Staff-Years (FY 2004):
2 professionals
1 research associate

Goals

The Antenna Theory and Applications project develops, refines, and extends measurement techniques to meet current requirements and to anticipate future needs for accurate antenna characterization.



Laser tracker configured on the NIST millimeter-wave planar near-field range. The laser tracker dynamically measures the precise position of the measurement probe during the near-field measurement scan.

Customer Needs

Microwave antenna hardware continues to become more sophisticated. We provide state-of-the-art measurement support for antennas and antenna systems. Current demands include:

Improved Accuracy — High-performance systems, especially those that are satellite-based, require maintenance of tighter tolerances.

Higher Frequencies — Millimeter-wave applications up to 500 gigahertz have been proposed.

Low-Sidelobe Antennas — Military and commercial communications applications increasingly require sidelobe levels of 50 decibels below peak (or better), a range where measurement by standard techniques is difficult.

Complex Phased-Array Antennas — Large, often electronically-steerable, phased arrays require special diagnostic tests to ensure full functionality.

***In Situ* and Remote Measurements** — Many systems cannot be transported to a measurement laboratory. Robust techniques are needed for on-site testing.

Production-Line Evaluation — Techniques are required that emphasize speed and economy, possibly at the expense of the ultimate accuracy.

RFID Reliability — RFID is being used in new applications such as inventory control and electronic passports. New methods are needed to assure reliability and security.

Evaluation of Anechoic Chambers and Compact Ranges — A number of widely used measurement systems rely on establishing a well-characterized test field. Near-field methods can be used to evaluate and analyze the quality of these test fields.

Technical Strategy

We seek to expand our frequency coverage for antenna calibrations to meet the demands of government and industry. A probe-position correction theory has been developed. By 2005, probe-position correction will be implemented at the NIST range by using a laser tracker to dynamically acquire position data. This will help us to maintain low uncertainties as we extend the frequency coverage of our calibrations.

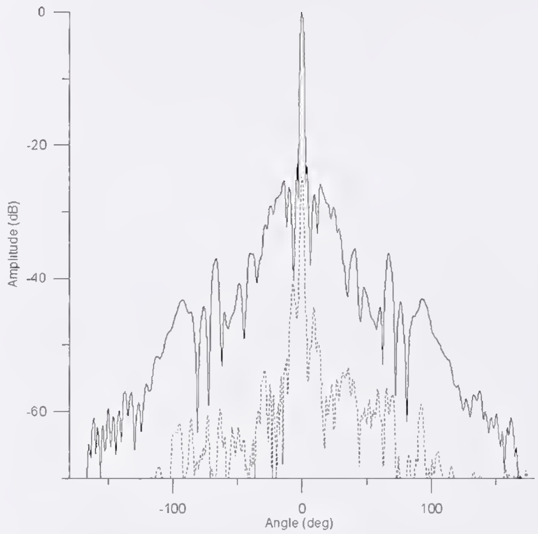
The near-field extrapolation method, developed at NIST, is an accurate technique to characterize the on-axis gain and polarization properties of antennas. Further improvement is still possible. We plan to extend the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm.

A thorough uncertainty analysis for planar near-field measurements has been previously developed. A similarly comprehensive uncertainty analysis is needed for spherical near-field measurements. We have completed a preliminary analysis and are working to refine the bounds.

In-situ near-field measurements of antenna systems are problematic because of the mechanical difficulties in maintaining position tolerances and because full spherical scans are typically not physically feasible. We have made significant progress in overcoming both these challenges and are working on the practical implementation of a deployable measurement system.

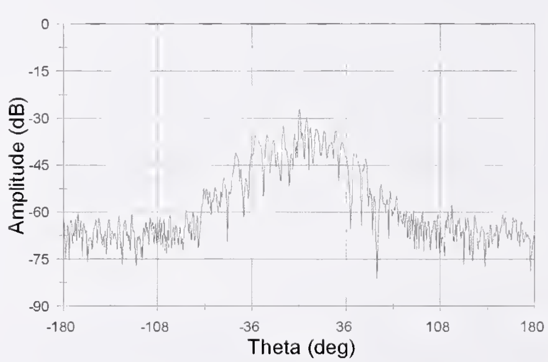
Accomplishments

■ **Multiple Reflections Uncertainty** — A method for estimating the uncertainty due to probe-antenna multiple reflections has been developed and documented.

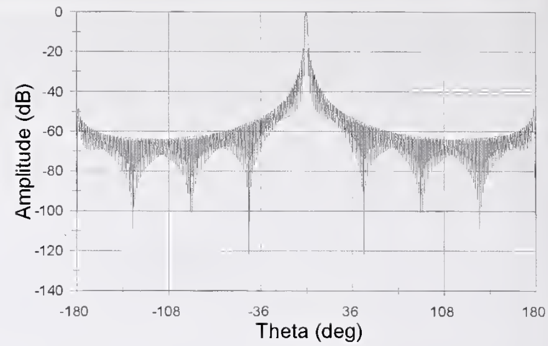


Estimated multiple reflection error (lower signal) compared to the antenna pattern for the φ = 90°.

■ **Probe-Position Correction** — A three-dimensional probe position-error correction scheme has been developed for spherical near-field scanning applications. This complements the three-dimensional probe-position software completed earlier for planar near-field scanning. Software is available to the public.

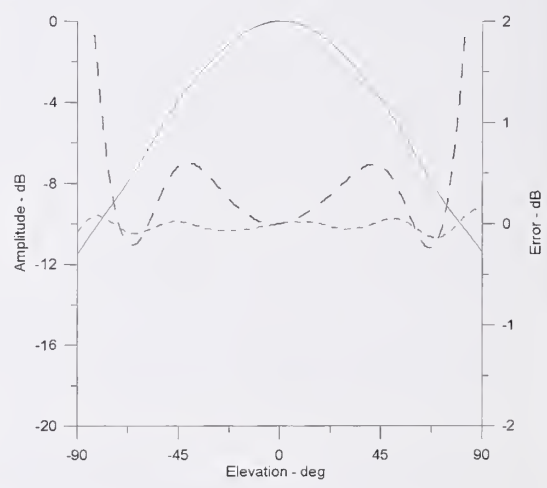


The far-field pattern computed for a maximum directivity antenna (N = 128), ignoring probe position errors.



The far-field pattern of a maximum directivity antenna (N=128) with position correction.

■ **Optimizing Results from Partial Scans** — A computer program has been completed to ameliorate the effects of missing data when only part of a sphere is scanned. If the missing data are set to zero the result is a sudden drop in the measured amplitude of the near field. When transformed to the far field, this results in ringing in portions of the far field. The new optimized method does a constrained least-squares fit by using forward hemisphere data and gain information to ensure a smooth transition to the back hemisphere. The smooth transition effectively eliminates the ringing in the far field.



Cylindrical waveguide probe: Deviations from the full-sphere pattern (errors) are shown for the truncated (long dash) and constrained least squares (short dash) methods. The full-sphere pattern is the solid line.

Short Courses

- NIST and the Georgia Institute of Technology annually offer an introductory course on antenna measurements. Every other year we present an in-depth technical course restricted to near-field methods that were pioneered at NIST.

Software

- Planar, cylindrical, and spherical near-field scanning applications algorithms are currently available. Probe position-correction software is available for the planar and spherical methods. The constrained least squares algorithm for partial sphere data is also available. Quiet-zone evaluation and imaging programs should be available soon.

External Recognition

- Mike Francis chairs the Antenna Standards Committee of the IEEE Antennas and Propagation Society.

- Mike Francis received the Antenna Measurement Techniques Association Distinguished Service Award in October 2004.

Recent Publications

J. Guerrieri, K. MacReynolds, M. Francis, R. Wittmann, and D. Tamura, "Practical Implementation of Probe-Position Correction in Planar Near-Field Measurements," Proc. Antenna Meas. Tech. Assoc., Atlanta, GA, pp. 356-359 (October 2004).

M. Francis, J. Guerrieri, K. MacReynolds, and R. Wittmann, "Estimating Multiple-Reflection Uncertainties in Spherical Near-Field Measurements," Proc. Antenna Meas. Tech. Assoc., Atlanta, GA, pp. 85-87 (October 2004).

R. Wittmann and M. Francis, "Spherical Scanning Measurements: Propagating Errors Through the Near- to Far-Field Transform," Proc. Antenna Meas. Tech. Assoc., Atlanta, GA, 74-79 (October 2004).

R. Wittmann, B. Alpert, and M. Francis, "Near-Field Spherical-Scanning Antenna Measurements with Nonideal Probe Locations," *IEEE Trans. Ant. Prop.* **52**, 2184-2186 (August 2004).

M. Francis and R. Wittmann, "Uncertainty Analysis for Spherical Near-Field Measurements," Proc. Antenna Meas. Tech. Assoc., Irvine, CA, pp. 43-45 (October 2003).

R. Wittmann, C. Stubenrauch, and M. Francis, "Spherical Scanning Measurements Using Truncated Data Sets," Proc. Antenna Meas. Tech. Assoc., Cleveland, OH, pp. 279-283 (November 2002).

R. Wittmann, B. Alpert, and M. Francis, "Spherical Near-Field Antenna Measurements Using Nonideal Measurement Locations," Proc. Antenna Meas. Tech. Assoc., Cleveland, OH, pp. 43-45 (November 2002).

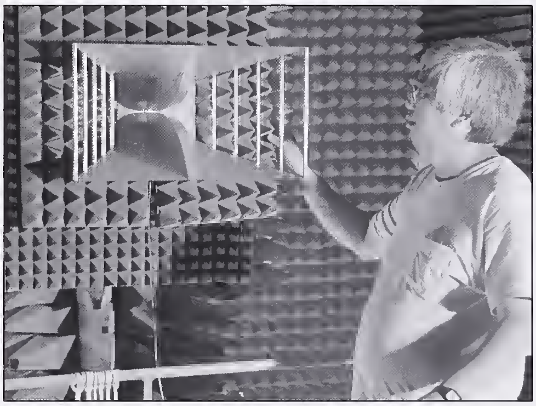
Antennas and Antenna Systems: Antenna Near-Field Measurements

Technical Contact:
Katie MacReynolds

Staff-Years (FY 2004):
2 professionals
1 technician
1 research associate

Goals

The Antenna Near-Field Measurements project serves as a national resource by providing antenna measurement services and traceability through calibrations. It support government and private industry programs, and maintains and develops the standards, methods, and instrumentation for antenna characterization of gain, polarization and pattern measurements.



Doug Tamura aligns a dual ridge horn for measurements.

Customer Needs

We continue to upgrade antenna metrology capability to meet evolving customer demands in the following areas:

Probe Characterization — Accurate probe characterization is fundamental to precise antenna measurements. We provide probe correction coefficients for use in planar, spherical and cylindrical near-field facilities.

Planar and Spherical Near-Field Measurements — These are required to accurately characterize large aperture, high-frequency antennas such as phased array and dish antennas used in satellite communications.

Antenna Standard Characterization — Industry and government require antenna standards for in-house antenna measurements.

Measurement Traceability — Program specifications often require NIST traceability.

Independent Verification of Antenna Parameters — Government and industry request measurements to verify that their measurement and analysis procedures produce the predicted and correct results.

Technical Support — Assistance on measurement techniques and analysis algorithms for antenna facilities that are implementing near-field measurements.

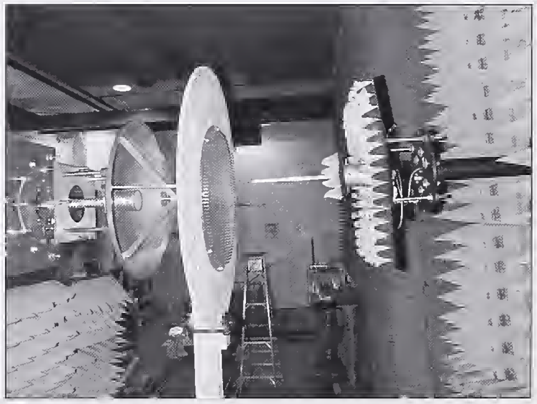
Technical Strategy

We currently maintain near-field antenna measurement standards and capabilities for frequencies from 1.5 to 110 gigahertz. The recent integration of a laser tracker system provides accurate information on probe position for use with position-correction algorithms. These improvements will help maintain low uncertainties as near-field measurement frequencies are increased in the future.

We are extending the frequency range of our extrapolation measurement capability. The new extrapolation range will provide on-axis probe characterization capability to complement near-field range antenna pattern measurements at millimeter wave frequencies.

We are performing an internal comparison on all three of the NIST near-field ranges — planar, cylindrical, and spherical — to verify performance and refine uncertainties. Our capability with all three types of ranges is unique.

We are providing reference antennas and measurements to improve radiometer calibrations in support of the National Polar-Orbiting Operational Environmental Satellite System (**NPOESS**). Anten-



Planar near-field measurements used to characterize radiometer phase retardation plate.

nas and retardation plates (polarizers) are being measured to better characterize radiometer performance. We plan to develop both calibration systems and standard sources.

Accomplishments

- **Antenna Calibrations** — We routinely perform antenna calibrations for external customers. Examples of recent measurements are:
  - WR-28 — Open-ended Waveguide Probe
  - WR-62 — Dual-port Linear Probe
  - WR-90 — 2 Standard Gain Horns
  - WR-137 — Standard Gain Horns
  - WR-42 — 3 Horn Lens Antenna
  - WR-22 — 3 Horn Lens Antenna
  - WR-28 — Cassegrain Dish Antenna
  - Broadband — 2 Dual Ridge Horns

Recent Publications

J. Guerrieri, K. MacReynolds, M. Francis, R. Wittmann, and D. Tamura, "Practical Implementation of Probe-Position Correction in Planar Near-Field Measurements," Proc. Antenna Meas. Tech. Assoc., Atlanta, GA, pp. 356-359 (October 2004).

J. Randa, A. Cox, D. Walker, M. Francis, J. Guerrieri, and K. MacReynolds, "Standard Radiometers and Targets for Microwave Remote Sensing," Int. Geoscience and Remote Sensing Symp. (IGARSS), Anchorage, AK (September 2004).

J. Guerrieri, K. MacReynolds, and D. Tamura, "Evaluation of a Radiometer Phase Retardation Plate Using Planar Near-Field Measurements," Proc. National URSI Meeting, Boulder, CO (January 2004).

J. Guerrieri, K. MacReynolds, and D. Tamura, "Radiometer Phase Retardation Plate Evaluation Using Planar Near-Field Antenna Measurements," Proc. Antenna Meas. Tech. Assoc., Irvine, CA (October 2003).

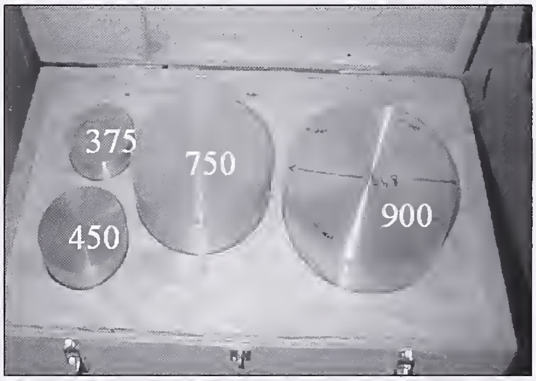
Antennas and Antenna Systems: Metrology for Radar Cross Section Systems

Technical Contact:
Lorant Muth

Staff-Years (FY 2004):
1 professional

Goals

The Metrology for Radar Cross Section Systems project assists the U.S. Department of Defense (**DOD**) and industrial radar cross section (**RCS**) measurement ranges to create and implement a National DOD Quality Assurance Program to ensure high quality RCS calibrations and measurements with stated uncertainties.



The basic cylinder set used to calibrate static RCS measurement systems in the frequency range of 2 to 18 gigahertz. The cylinders are made of aluminum, and are manufactured to a tolerance of ± 0.127 millimeter.

Customer Needs

RCS measurements on complex targets, such as aircraft, ships, and missiles, are made at different types of RCS measurement ranges, including compact ranges (indoor static), and outdoor static or dynamic facilities. Measurements taken at various ranges on the same targets must agree with each other within stated uncertainties to increase confidence in RCS measurements industry wide. Although the sources of uncertainty are well known, a comprehensive determination of the magnitudes of uncertainties in RCS calibrations require well-formulated procedures that measurement ranges can use to determine their uncertainties. Customer needs include:

Calibration Artifacts — RCS users need improved calibration artifacts that are dimensionally traceable and calculable, and exhibit wide dynamic range.

Calibration Procedures — Calibration procedures and data analysis techniques are needed to minimize range uncertainties at both government and industrial RCS ranges. The implementation of improved procedures and the determination of range uncertainties at every RCS measurement range are essential if the U.S. RCS industry is to maintain its world leadership.

Technical Strategy

The complex measurement systems and measurement practices at RCS ranges should be documented uniformly throughout the industry so that meaningful comparison of capabilities and important range-to-range differences are recognized. The framework of a RCS Range Book, in the context of a DOD RCS Self-Certification Program, is used to ensure community-wide compliance.

We provide RCS Range Book reviews for the DOD and industrial RCS ranges. These in-depth reviews provide guidance to the RCS community as they pursue their industry-wide certification program. The uncertainty analyses pursued by the U.S. RCS ranges are based on the pioneering work by NIST in this area.

We have continued to work closely with selected RCS ranges to develop and standardize procedures to determine RCS calibration and measurement uncertainty for both monostatic and bistatic RCS measurements. Fully polarimetric calibration procedures are also being studied.

To support these research activities we have recommended an expanded set of RCS calibration cylinders to calibrate the system at various signal levels of interest using a single artifact. To support polarimetric calibration research, we recommended a set of calibration dihedrals that can be used to determine system parameters needed to analyze polarimetric calibration data.

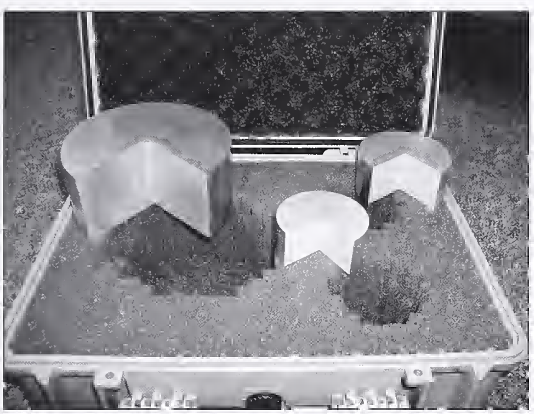
We seek to fully assess the technical merit and deficiencies of existing calibration and measurement procedures, data-analysis techniques, and uncertainty analysis. We plan to publish recommendations for improvements in these areas. We plan to further explore known problems in areas such as dynamic sphere calibration, polarimetric calibration, and bistatic RCS calibration.

The annual RCS Certification Meeting held at NIST-Boulder provides a forum for the RCS community to discuss procedural and technical issues on an ongoing basis.

Accomplishments

■ **Cylinder Calibration Set** — The RCS community has adopted a basic cylinder calibration set to test the calibration integrity of monostatic RCS systems. Computed radar cross sections for the cylinder set have been obtained. These 4 cylinders have been measured at a number of government and industrial measurement ranges, with agreement with the theoretical RCS of better than 0.5 decibels. These comparisons demonstrate good repeatability; however, we need more robust independent measurement procedures to determine the measurement uncertainties.

■ **Dihedral Calibration Set** — We designed and manufactured a set of calibration cylinders with dihedral cutouts that can be used to calibrate a RCS range within a large dynamic range rather than at a single signal level, thereby improving calibration accuracy within the measurement interval. These artifacts should be useful in a nationwide measurement-comparison program.



RCS calibration cylinders with dihedral cutouts make it possible to calibrate a RCS measurement system over a large dynamic range.

■ **RCS Uncertainty Analysis** — We have completed a measurement-based RCS calibration uncertainty analysis for the Etcheron Valley Range, NAVAIR, China Lake, CA. This study determined the calibration uncertainty bounds without having to rely on statistical model assumptions that may not be valid for RCS calibrations and measurements.

■ **Polarimetric Calibrations** — RCS ranges have reported less than satisfactory results with existing polarimetric calibration procedures. We developed a more robust calibration procedure wherein full polarimetric data are obtained using a dihedral rotating around the line-of-sight to the radar. The new procedure allows us to improve the signal-to-noise ratio and check for alignment problems by exploiting the symmetry properties of the dihedral.

Recent Publications

L. Muth, D. Diamond, and J. A. Lelis, "Uncertainty Analysis of Radar Cross Section Calibrations at Etcheron Valley Range," NIST Technical Note 1534 (2004).

L. Muth and T. Conn, "Phase-Dependent RCS Measurements in the Presence of Outliers," Proc. Antenna Meas. Tech. Assoc., Irvine, CA, pp. 410-415 (October 2003).

L. Muth, "Calibration of nonreciprocal radar systems," Proc. International Symposium on Antennas, Nice, France, Vol. 2, pp. 257-260 (November 2002).

L. A. Muth, "Phase Dependence in Radar Cross Section Measurements," NIST Technical Note 1522 (2001).

Electromagnetic Compatibility: Reference Fields and Probes

Technical Contact:
Keith Masterson

Staff-Years (FY 2004):
2 professionals
2 technicians

Goals

The Reference Fields and Probes project develops methods and techniques for establishing continuous-wave electromagnetic (**EM**) reference fields and transfer probes for frequencies to 100 gigahertz. It maintains the capability to provide antenna, probe, and field measurements with international compatibility and traceability to NIST in support of U.S. industry. Although most present applications utilize spectra in the 1 megahertz to 10 gigahertz range, systems such as automotive collision avoidance radars that operate up to nearly 100 gigahertz are being developed.

Antenna under test at NIST anechoic chamber facility.

Customer Needs

Based on the principles of "one product, one technically valid international standard, one conformity assessment" (1998 MSL Strategic Plan), industry requires EM field measurement capabilities and transfer probes that are traceable to NIST in order meet multinational compliance requirements and reduce barriers to worldwide acceptance of U.S. products. We address these needs with the following:

Reference Fields — Well defined EM reference fields are necessary for the calibration of antennas and probes. They are also needed for research and development to increase measurement accuracy and spectral range as will be necessary to support the future needs of U.S. industry and private test laboratories.

Field Probes — Accurate field probes are needed by government and industry to define EM field levels. U.S. defense and homeland security agencies rely heavily on EM systems for sensors and strategic communication. New probes need to be developed for the ever expanding range of EM environments.

Probe Calibrations — Field probe calibrations are costly. Techniques to reduce calibration costs are needed, especially for applications that require multiple probes and frequent recalibration.

Technical Strategy

We maintain an integrated effort both to generate standard reference fields and to develop the probes required for their accurate measurement. The two efforts complement each other and allow cross checking in order to reduce the uncertainties inherent in each effort as well as to transfer calibration capabilities to other test laboratories and facilities. As instrumentation and electronics achieve higher clock rates, measurements are needed at higher frequencies. We are working both to extend current techniques and facilities to higher frequencies and to develop new test methods to increase accuracy and reduce measurement costs. In this context, we plan to develop improved methods for measuring radio frequency (**RF**) emissions above 1 gigahertz.

Open-area test site (**OATS**) facilities are accepted as standard sites for electromagnetic compatibility (**EMC**) emissions measurements. Previous comparisons of EMC emissions measurements at various industrial sites showed large variations from site to site. Development of a service to quantify the output from various reference emitters would address site variations. A reference emitter measurement service for 30 to 1000 megahertz has been offered. We work closely with the American National Standards Institute (**ANSI**) to further improve OATS methods.

Fully anechoic chamber (**FAC**) facilities are accepted as standard sites for free-space measurements. By 2006, we expect to improve techniques for antenna far-field characterization in our chamber for frequencies up to 18 gigahertz. The chamber is also being evaluated for EMC product testing up to 40 gigahertz.

Closed test systems such as transverse electromagnetic (**TEM**) cells have been widely adopted for testing small antennas, sensors, and probes, but are normally limited by geometrical constraints to frequencies below 1 gigahertz. We are currently constructing a new closed-cell system that utilizes a co-conical geometry that can be used to test such devices up to 45 gigahertz. The test volume of this system is large enough to calibrate several probes at once. EM modeling and analysis using numerical techniques such as finite-difference time-domain are used to predict system performance for multiple probes.

We have developed photonic probes that transmit analog signals along optical fibers to preserve both phase and amplitude of high-frequency and pulsed signals, and to reduce errors caused by scattering or pickup in metallic leads. We will upgrade our standard RF dipole with optical fiber links to help reduce the measurement uncertainties arising from the increase in ambient fields at our OATS. At terahertz frequencies, optical fibers hold a clear advantage for signal transmission from a probe head to receiving electronics. By 2006 we plan to demonstrate techniques for a fiber-based 100 gigahertz probe system.

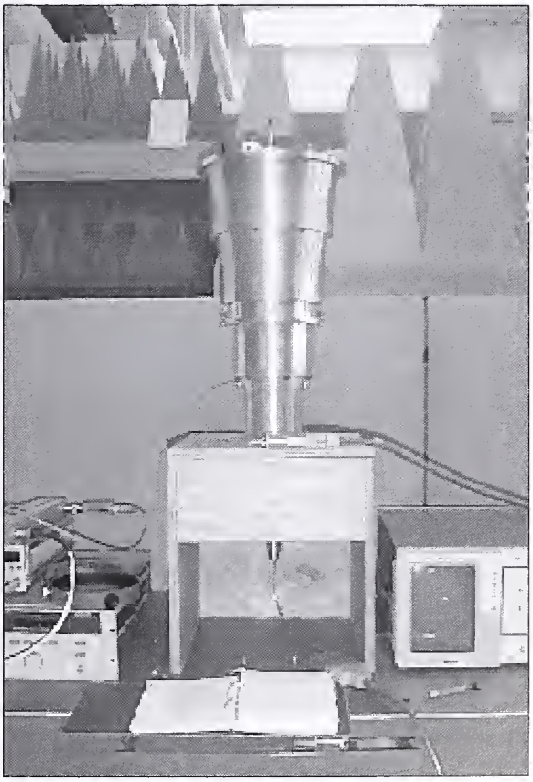
Measurements performed using different equipment and facilities such as OATS, TEM cells, FAC and semi-anechoic facilities often yield different results. We will focus on systematically investigating methods to reducing these variations and improve congruity within the U.S. industrial community. We will provide technical information and guidance to standards organizations to help correlate measurements between various EMC test facilities by 2006. We will also cooperate with the national test laboratories of our international trading partners to perform round-robin testing and intercomparison of various standard antennas and probes. This assures international agreement in their performance and reduces the uncertainties in the areas of metrology that affect international trade.

Accomplishments

- **OATS Qualification above 1 Gigahertz** — Cooperative measurements with U.S. national laboratories provided key data for new EMC standards work above 1 gigahertz. In particular, methods that qualify OATS above 1 gigahertz were investigated as part of an ANSI C63 effort. Studies were done on scattering objects and the effects of test environments on antenna measurements.

- **Probe Calibrations** — Calibrations were performed on probes/antennas for several companies and/or government agencies covering the frequency range of 10 kilohertz to 45.5 gigahertz using TEM cell and anechoic chamber test facilities. Field levels varied from 1 to 200 volts per meter.

- **Co-Conical Field Generation System** — A feasibility study on a co-conical field generation system for rapid, cost-effective probe calibration was completed. A full turnkey facility development has been designed. This system will be used as a standard-field generation system for probe calibrations in the frequency range from 10 megahertz to 45 gigahertz. This effort is currently sponsored by the U.S. Air Force.



Prototype co-conical field generation system.

- **Electro-Optic Probe** — A standard RF dipole with electro-optic coupling that covers a range from 10 megahertz to 1.5 gigahertz was fabricated.

- **E and H Field Probe** — A loop antenna with integrated photonics and controls to simultaneously measure E and H fields up to 1 kilovolt per meter is being developed.

Double gap loop antenna system for simultaneous measurement of E and H.

Recent Publications

J. Hamilton and K. Masterson, "Accurate Bias Point Control for an Electrically Isolated Mach-Zehnder Interferometric Modulator via an Analog Optical-Fiber Link," Proc. SPIE, Denver, CO, Vol. 5531, pp. 323-331 (August 2004).

P. Wilson, C. Holloway, and G. Koepke, "A Review of Dipole Models for Correlating Emission Measurements Made at Various EMC Test Facilities," Proc. 2004 IEEE Int. Symp. Electromagn. Compat., Santa Clara, CA, pp. 898-901 (August 2004).

K. Masterson, "Photonic Probes for Intense Electromagnetic Fields." Proc. 6th Ann. Directed Energy Symp., Albuquerque, NM (October 2003).

M. Candidi, C. Holloway, P. Wilson, and D. Camell, "Comparison of Radiated Emission Measurements for 500 MHz to 2 GHz in Various EMC Facilities," Proc. 2002 European Symp. Electromagn. Compat., Sorrento, Italy, pp. 823-828 (September 2002).

P. Wilson, D. Camell, C. Holloway, R. Johnk, G. Koepke, J. Ladbury, K. Masterson, and A. Ondrejka, "Electromagnetic Compatibilty Research at NIST, Boulder," IEEE EMC Society Newsletter, Issue 194, pp. 19-28 (Summer 2002).

J. Ladbury and D. Camell, "Electrically Short Dipoles with a Nonlinear Load: A Revisited Analysis," *IEEE Trans. Electromagn. Compat.* **44**, 38-44 (February 2002).

C. Weil, D. Camell, D. Novotny, R. Johnk, and A. Ondrejka, "New Techniques for Calibrating Across-the-Road Traffic Radars," Proc. 27th URSI General Assembly, Maastricht, The Netherlands, paper AB1.O.9 (August 2002).

Electromagnetic Compatibility: Complex Fields

Goals

The Complex Fields project develops and maintains measurement methods to quantify fields in complex environments, such as electrically large cavities and highly nonuniform boundaries. Applications include the reverberation chamber, the statistics of electromagnetic fields in rooms and buildings, the communications needs of first responders, measurements of shielding effectiveness of advanced composites, coupling to large scale systems and components, coupling to biological objects, advanced numerical methods, and metamaterials. These efforts support industry and government agencies, national and international standards, healthcare, homeland security, and nanotechnology.

Christopher Holloway tests a composite medium consisting of insulating magneto-dielectric spherical particles embedded in a background matrix for double negative index behavior. © Geoffrey Wheeler

Customer Needs

Large, complex systems located in complex field environments need to be tested for electromagnetic compatibility (**EMC**). Electromagnetic interference (**EMI**) affects U.S. competitiveness (through trade restrictions and regulations), national security, health, and safety. EMC regulations and requirements constitute 1 to 10 percent of the total U.S. product costs and can cause delays to market. We are providing research and support to address a number of critical areas:

Reverberation Chambers — Reverberation chambers are used to test large complex systems at high frequencies. Users of reverberation chambers need better models of statistical parameters, improved chamber and stirrer designs, test object models, and guidance for translating reverberation chamber technology into national and international standards.

Shielding of Advanced Composites — Shielding effectiveness of advanced composites cannot be readily tested with existing methods (*e.g.*, ASTM coaxial fixture). New methods are needed, such as the use of nested reverberation chambers.

Coupling to Biological Objects — The increased use of wireless devices in scattering-rich environments is creating questions about the effects of exposure of humans and animals to electromagnetic fields. These conditions need to be replicated in controlled experiments.

First Responder Communications — First responders to emergency situations encounter difficult communications scenarios. There is a need to understand propagation in a wide variety of environments, including collapsed buildings.

Complex Boundaries — The interface between complex media is a difficult modeling and measurement challenge. Advances at both the macro- and micro-scale (nanotechnology) are needed.

Technical Strategy

Our goal is to develop and evaluate reliable and cost-effective standards, test methods, and measurement services related to complex electromagnetic fields for EMC of electronic devices and other applications in health, defense, and homeland security. This includes investigating new applications for existing test facilities as well as improving methods for evaluating the critical characteristics of support hardware, such as antennas, cables, connectors, enclosures, and absorbing material.

Reverberation chambers are increasingly a key tool for EMC testing in the gigahertz frequency range. The recent publication of IEC61000-4-21 on reverberation chamber test methods will increase usage. We have played a leading role in developing reverberation chamber technology. We continue to develop models for the statistical behavior of

Technical Contact:
Galen Koepke

Staff-Years (FY 2004):
3 professionals
6 research associates

the fields in the test volume and near the boundaries. While the typical target for a reverberation chamber is a Rayleigh field distribution, multiple-input/multiple-output (**MIMO**) system testing requires a Ricean field distribution. We will investigate methods to accurately control the ratio between direct and indirect coupling for MIMO and other test applications. Probes are traditionally calibrated in highly controlled reference fields. We will investigate whether the large volume of a reverberation chamber can be used to simultaneously calibrate a large number of field probes. We are developing analytical models of test-object directivity. We will continue to experimentally test these models and transfer results to committees developing standards for reverberation chamber.

Advanced composites offer weight and performance advantages over metals and are increasingly being used in aerospace and other applications. Plastics inherently provide no significant shielding to electromagnetic fields. Plastics can be "metalized" by introducing conducting fibers; however, this may affect mechanical performance. There is a need to reliably test for the EM shielding properties of advanced composites so that manufacturers can find the right balance between electrical and mechanical performance for a particular application. We are investigating the use of nested reverberation chambers to address this challenge. We are investigating better statistical descriptors for the shielded fields to more accurately define shielding effectiveness in complex coupling environments.

The proliferation of wireless devices means increased exposure of humans to electromagnetic fields. Testing for the possible effects on health due to chronic exposure is needed. We recently completed a study on the use of a reverberation chamber to expose large number of phantoms to a controlled EM field. The phantoms simulated adult rodents. The study showed good exposure uniformity for a population of up to 250 phantoms in a moderately sized chamber. The National Institutes of Health (NIH) plans to conduct a long-term study on rodents using the reverberation chamber method. We will continue to investigate the coupling of fields to biological materials. We will investigate whether lossy materials that heat in an EM field can be developed as an alternative to field probes for chamber qualification and monitoring.

First responders need reliable communications in emergency scenarios. Disaster scenarios and terrorist attacks may result in scenarios where responders or citizens are trapped in collapsed or blocked buildings. The propagation of signals in the bands used by first-responder radios and cellular telephones needs to be investigated. We have performed unique experiments to define communications links in buildings prior, during, and after demolition. These data will give invaluable insight into the communications challenges faced by first responders. We are additionally investigating alternative methods to detect and locate trapped persons.

Meta-materials (*i.e.*, engineered or man-made materials) have received considerable interest in recent years. Metamaterials are commonly engineered by arranging a set of scatterers throughout a region of space in a specific pattern so as to achieve some desirable bulk behavior. Examples of electromagnetic metamaterials are artificial dielectrics, photonic bandgap structures, and frequency-selective surfaces. Recently there have been studies on the properties and potential applications of double-negative (**DNG**) materials. We are investigating a composite medium consisting of insulating magneto-dielectric spherical particles embedded in a background matrix to achieve DNG behavior. We have shown that the effective permeability and permittivity of the mixture can be simultaneously negative for wavelengths where the spherical inclusions are resonant.

We work closely with national and international standards bodies to transfer experimental and theoretical results and to improve test methods for large, complex systems. We plan to continue participation in various IEC, CISPR, ANSI, SAE and IEEE standards committees related to EMC test methods.

Accomplishments

- **Probe Response Model** — An improved response model for a diode-based electric field probe was developed. The model is being used to improve probe calibrations, particularly in a reverberation chamber where dynamic range is large.

- **Phantom Study** — The electric field statistics in a heavily loaded reverberation chamber were evaluated and compared to the empty-chamber statistics. The load consisted of phantoms (water bottles) filled with tissue-simulating liquid. Whole-body average specific absorption rate (SAR) in the phantoms was also determined via direct (temperature-increase) and indirect (insertion-loss) measurements. The results support the use of a reverberation chamber for animal exposure studies.

- **Propagation in Collapsed Buildings** — Two experimental studies on signal propagation in buildings prior, during, and after demolition were completed. These experiments provide invaluable data on first-responder communication challenges.

- **Effective Boundary Conditions** — Effective boundary conditions for thin films with applications to active materials such as frequency-tunable surfaces have been derived and published.

Recent Publications

J. Baker-Jarvis, P. Kabos, and C. L. Holloway, "Nonequilibrium Electromagnetics: Local and Macroscopic Fields and Constitutive Relationships," *Phys Rev E* **70**, 036615/1-13 (September 2004).

C. Holloway, M. Mohamed, and E. Kuester, "Reflection and Transmission Properties of a Metafilm with Application to a Controllable Surface Composed of Resonant Particles," *IEEE Trans. Electromagn. Compat.,* in press.

C. Holloway, M. Sarto, and M. Johansson, "Analyzing Carbon Fiber Composite Materials with Equivalent-Layer Models," *IEEE Trans. Electromagn. Compat.,* in press.

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Electromagnetic Compatibility: Time-Domain Fields

Technical Contact:
Robert Johnk

Staff-Years (FY 2004):
2 professionals
1 technician
1 research associate

Goals

The Time-Domain Fields project develops basic metrology and measurement techniques for a wide variety of applications such as antenna and sensor calibrations, evaluation of electromagnetic compatibility (**EMC**) measurement facilities, shielding performance of aircraft, nondestructive testing of electrical material properties, precise generation of standard fields, and detection of signals and threats.

Evaluation of a U.S Air Force early-warning aircraft using a portable NIST time-domain measurement system.

Customer Needs

Time-domain field methods use time windowing to eliminate unwanted signals. These methods find application to problems that cannot readily be evaluated using traditional continuous-wave radiated tests. In particular, time-domain methods allow for localization of large systems and for testing in highly cluttered environments. Customer needs include:

Reflection Properties — EMC test sites, such as anechoic chambers and open area test sites use absorbing and low-reflectivity materials to achieve performance. The reflectivity of these materials needs to be accurately characterized over a wide frequency range, possibly *in-situ*.

Shielding Effectiveness — Time-domain signals can be used to investigate the shielding effectiveness of large, complex geometries. Aircraft can be tested *in situ*, either over tarmac or in a hanger.

Propagation in Buildings — Buildings present complicated propagation environments. Communications systems need to know how waves couple through differing building materials and how waves couple from the exterior to interior and between interior locations.

Ultra-Wideband Systems — Ultra-wideband systems are being proposed to increase capacity and to address advanced communications needs. Antenna characteristics and link performance need to be accurately determined.

Technical Strategy

We develop measurement tools to both generate and receive ultrawideband radiated signals. We recently completed a large cone and ground plane facility. This facility can be used to generate well defined pulse fields for sensor calibration up to 20 gigahertz, antenna calibration and system characterization. We used extensive numerical simulations to optimize the feed and cone sections to achieve very high performance levels.

We have been a leader in developing transverse electromagnetic (**TEM**) horn antennas for receiving ultra-wideband signals. These antennas have very linear phase characteristics and are able to accurately preserve time-domain traces. We are planning to develop a set of design guidelines to transfer TEM horn technology.

The TEM horns are the basis of a field-deployable system for transmitting and receiving time-domain fields. The system uses optical fiber links to achieve high isolation and dynamic range. The system has been successfully applied to the evaluation of the shielding effectiveness properties of commercial and military aircraft. These efforts have assisted U.S. manufacturers and the U.S. Department of Defense (**DOD**) to improve flight safety and reduce the vulnerability of aircraft to electromagnetic interference and threats.

We are applying time-domain techniques to develop a database of the electrical properties of building materials in support of homeland security goals. The database will help first responders develop communications systems that will improve performance in emergency situations. We are collaborating on the use of genetic algorithms to accurately extract electrical parameters from time-domain reflection and transmission data.

We have supported industry and standards groups in assessing the performance of electromagnetic facilities such as anechoic and semi-anechoic chambers, shielded rooms, reverberation chambers, and open area test (**OATS**) facilities. The performance of microwave absorbers has been measured. Many facilities use low-reflectivity material for test object support and weather protection. We are helping to develop time-domain-based test methods to determine the effects of "reflectionless" materials, of the type specified in many radiated test standards, on site ability to perform ultrawideband RCS measurements.

Accomplishments

- **Aircraft Shielding** — A unique, leading-edge portable measurement systems for the evaluation of coupling to complex aircraft environments has been developed. The system has been used to evaluate a U.S. Air Force early-warning aircraft and a Boeing 767 commercial aircraft. An evaluation of a Boeing 737-200 aircraft at the Federal Aviation Administration (**FAA**) Technical Center in Atlantic City, New Jersey is planned. The data from this effort are public domain and will be disseminated to the aircraft testing community.

Evaluation of a commercial aircraft using a portable NIST time-domain measurement system.

- **Complex Cavity Modeling** — Numerical models of complex cavities have been developed to facilitate understanding of measurements performed in aircraft environments. This work is sponsored by the FAA.

- **Building Materials Characterized** — A free-field materials measurement system for the evaluation of building materials has been developed.

- **EMC Facilities Tested** — Several EMC facilities have been tested. The reflections from a fiberglass shelter were characterized and shown to be significant. Perturbations due to a turntable at a test site were measured and shown to be higher than anticipated.

Recent Publications

R. Johnk, D. Novotny, C. Grosvenor, N. Canales, and J. Veneman, "Time-domain measurements of radiated and conducted ultrawideband emissions," *IEEE Aerospace and Electronic Systems Magazine,* in press.

D. Novotny, C. Grosvenor, R. Johnk, and N. Canales, "Panoramic, Ultrawideband, Diagnostic Imaging of Test Volumes," Proc. 2004 IEEE Int. Symp. Electromagn. Compat., Santa Clara, CA, pp. 25-28 (August 2004).

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Magnetodynamics

Technical Contact:
Tom Silva

Staff-Years (FY 2004):
2 professionals
3 research associates
1 guest researcher

Goals

This project develops instruments, techniques, and theory for the understanding of the high-speed response of commercially important magnetic materials. Techniques used include linear and nonlinear magneto-optics and pulsed inductive microwave magnetometry. Emphasis is on high-frequency (above 1 gigahertz), time-resolved measurements for the study of magnetization dynamics under large-field excitation. Research addresses the nature of coherence and damping in ferromagnetic systems and their effects on the fundamental limits of magnetic data storage. Research on spin-electronic systems and physics concentrates on spin-momentum-transfer oscillators (see section on Spin Electronics) and nuclear spin polarization in semiconductors. The project provides results of interest to the magnetic disk drive industry, developers of magnetic random-access memory, and the growing spin-electronics community.

Mike Schneider next to cryogenic and room-temperature pulsed inductive microwave magnetometers.

Customer Needs

Advances in magnetic information storage are vital to economic growth and U.S. competitiveness in the world market for computer products and electronic devices. Our primary customers are the magnetoelectronics industries involved in the fabrication of magnetic disk drives, magnetic sensors, and magnetic random-access memory (**MRAM**).

Data-transfer rates are increasing at 40 percent per year (30 percent from improved linear bit density, and 10 percent from greater disk rotational speed). The maximum data-transfer rate in nanometric devices is currently 200 megabytes per second, with data-channel performance of over 1 gigahertz (in the microwave region), with corresponding magnetic switching times of less than 1 nanosecond. At these rates, a pressing need exists for an understanding of magnetization dynamics, and measurement techniques are needed to quantify the switching speeds of commercial materials.

The current laboratory demonstration record for storage density is over 30 gigabits per square centimeter (200 gigabits per square inch). How much further can longitudinal media (with in-plane magnetization) be pushed? Can perpendicular recording, patterned media with discrete data bits, or heat-assisted magnetic recording extend magnetic recording beyond the superparamagnetic limit at which magnetization becomes thermally unstable? We are developing the necessary metrology to benchmark the temporal performance of new methods of magnetic data storage.

Use of polarized spins in semiconductors is a new direction in electronics that promises to revolutionize telecommunications and information processing. It is based on the manipulation and control of the quantum-mechanical spin of a semiconductor's charge carrier. It holds the promise of extending telecommunications frequencies into the terahertz regime. The frequency performance of conventional devices based on charge transfer is limited by electron velocities, charge-transfer times, and carrier mobilities, whereas the electron spin has no fundamental frequency limitation as long as coherence can be preserved. The electron-spin degree of freedom forms the most fundamental quantum oscillator.

Technical Strategy

Nanomagnetodynamics — Our technical strategy is to identify future needs in the data-storage and other magnetoelectronic industries, develop new metrology tools, and do the experiments and modeling to provide data and theoretical underpinnings. We concentrate on two major problems in the magnetic-data-storage industry: (1) data-transfer rate, the problem of gyromagnetic effects, and the need for large damping without resorting to high fields, and (2) storage density and the problem of thermally activated reversal of magnetization. This has led to the development of instrumentation and experiments using magneto-optics and microwave circuits. Microwave coplanar waveguides are used to deliver magnetic-field pulses to materials under test. In response, a specimen's magnetization switches, but not smoothly. Rather, the magnetization vector undergoes precession. Sometimes, the magnetization can precess nonuniformly, resulting in the generation of spin waves or, in the case of small devices, incoherent rotation. We use several methods to detect the state of magnetization as a function of time. These include the following:

- The magneto-optic Kerr effect (**MOKE**) makes use of the rotation of polarization of light upon reflection from a magnetized film. We have used MOKE with an optical microscope to measure equilibrium and nonequilibrium decay of magnetization in recording media.

- The second-harmonic magneto-optic Kerr effect (**SH-MOKE**) is especially sensitive to surface and interface magnetization. We have used SH-MOKE for time-resolved vectorial measurements of magnetization dynamics and to demonstrate the coherent control of magnetization precession.

- In our pulsed inductive microwave magnetometer (**PIMM**), the changing magnetic state of a specimen is deduced from the change in inductance of a waveguide. This technique is fast, inexpensive, and easily transferable to industry. It may also be used as a time-domain permeameter to characterize magnetic materials. Since the development of the PIMM at NIST, similar systems have been built at several industrial research laboratories and universities.

While these instruments have immediate use for the characterization of magnetic data-storage materials, they are also powerful tools for the elucidation of magnetodynamic theory. The primary mathematical tools for the analysis of magnetic switching data are essentially phenomenological. As such, they have limited utility in aiding industry in its goal to control the high-speed switching properties of heads and media. We seek to provide firm theoretical foundations for the analysis of time-resolved data, with special emphasis on those theories that provide clear and unambiguous predictions that can be tested with our instruments.

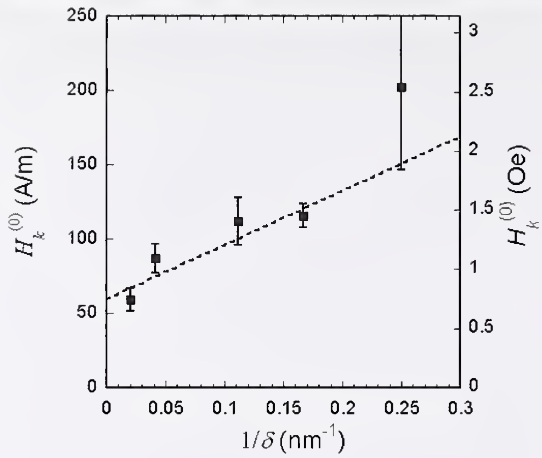
Polarized Spins in Semiconductors — The spin precession of charge carriers in semiconductor hosts has significant potential for telecommunications applications. Unlike the case of conventional semiconductor switching, the frequency of spin precession is not fundamentally limited by the physical thickness of dielectric spacers. We are investigating optically generated spin populations in semiconductors and novel magnetic/semiconductor heterostructures of interest to the telecommunications industry. To enable future applications of polarized spins in semiconductors, such as ultra-high-frequency oscillators, our goal is to obtain and measure coherent spin dynamics in metal/semiconductor heterostructures.

Recent advances in spin-based semiconductor devices have demonstrated that coherent spin precession can be maintained for hundreds of nanoseconds in III-V semiconductors and hundreds of microseconds in silicon. The precession frequency can be controlled by applied magnetic fields, gate voltages, and modulation doping techniques. Terahertz precession has been observed in Mn-doped InAs heterostructures with no applied magnetic fields. Modulation of the electron *g*-factor has been observed in the presence of electric fields that move the spin packets between regions of different *g*-factors, *e.g.*, GaAs and AlGaAs.

We are investigating methods of measuring small numbers of spins in semiconductor devices and spin traps. Developing this metrology will be essential to the development of methods to control and manipulate small numbers of spins in a spin circuit. We have developed a pulsed-laser technique to pump and probe spin populations in semiconductors at cryogenic temperatures. The spin population is measured using the rotation of linear polarized light that is transmitted through a bulk sample. In addition to exploring spin dynamics in semiconductors, we are studying metallic devices that use spin-momentum transfer to induce coherent precession (see section on Spin Electronics).

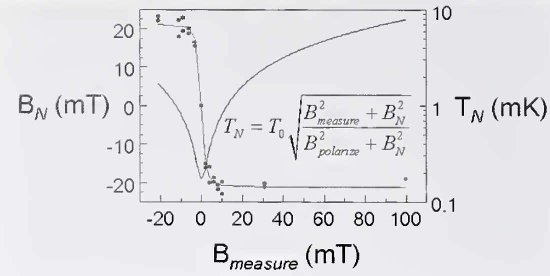
Accomplishments

- **Surface Dependence for Rotatable Anisotropy** — We found that there is a surface contribution to the rotatable anisotropy in Permalloy. Contributions to the magnetic anisotropy for which the magnetization direction itself is the source of symmetry breaking are generally categorized as "rotatable anisotropy." In a comprehensive study intended to determine the physical origins of rotatable anisotropy in single-layer Permalloy films, the pulsed inductive microwave magnetometer was successfully used to measure the anisotropy energy density as a function of magnetization angle. We found that the component of the energy density that is independent of magnetization angle is inversely proportional to film thickness, as expected if the source of the effect is associated with surfaces and interfaces. These results have significant implications for data storage applications, where the thickness of the magnetic sensor layer in a disk drive must be substantially reduced to accommodate higher areal densities of data.



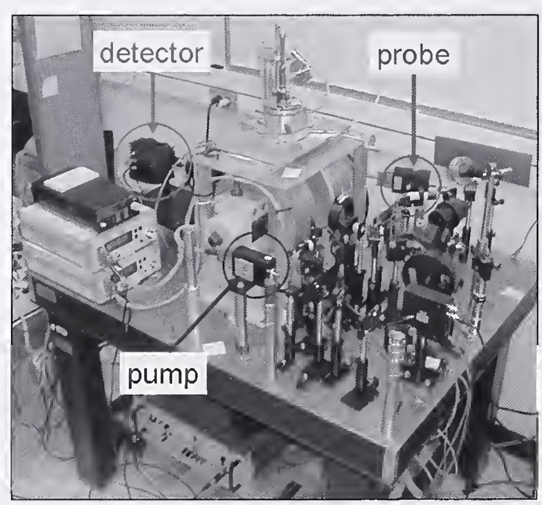
Rotatable anisotropy $H_k^{(0)}$ for Permalloy, as a function of film thickness δ. The linear dependence on inverse film thickness is evidence that the rotatable anisotropy is a surface effect. The presence of such rotatable anisotropy enhances the bandwidth of ultrathin Permalloy layers, but at the expense of the susceptibility.

■ **Nuclear Spin Reversal Using a Swept DC Field** — We observed a reversal of nuclear spins in GaAs due to adiabatic cooling effects when an applied magnetic field is swept through zero. Nuclear polarization is generated by illuminating a GaAs sample with circularly polarized light from a laser diode. The steady-state nuclear polarization is altered by the nonequilibrium electron spin population excited with the laser diode. Detection of the nuclear spin polarization is achieved by monitoring the electron spin precession frequency shift due to the hyperfine effect. We found that the polarization of nuclei that were oriented in an applied field of 80 kiloamperes per meter was switched when the applied field was swept within the T_1 time for the nuclear spin states. When the applied field is reduced on a scale shorter than the T_1 time, the entropy of the nuclear spin system is conserved, requiring a reduction of the nuclear spin temperature. However, at sufficiently low nuclear spin temperatures, inter-spin interactions dominate and the nuclear spin temperature is minimized. The field at which the nuclear spin system depolarizes is a direct measure of the internuclear interaction strength. We have found that the interspin interactions are an order of magnitude greater than previously observed for p-doped GaAs. Efforts are now under way to determine whether these interactions are sufficient to induce a quantum phase transition at sufficiently low nuclear spin temperatures.



Hyperfine field H_N and effective nuclear temperature T_N for dynamic nuclear polarization in GaAs. The hyperfine field is quenched near zero applied field, then reverses sign as field is swept through zero. These results indicate that the nuclear spin system is adiabatically cooled as the applied field is ramped to zero. The reversal of the hyperfine field is a direct result of the adiabatic nature of the measurement.

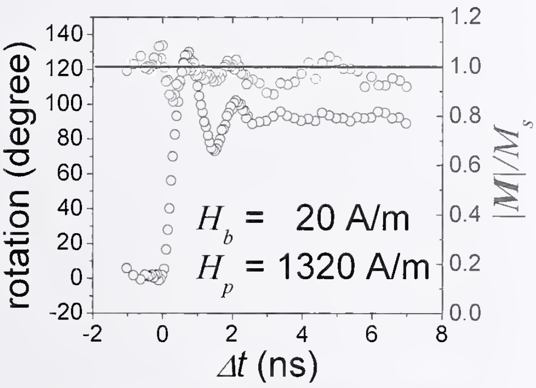
■ **Pump-Probe Faraday Rotation Magnetometer Using Two Diode Lasers** — A pump-probe Faraday rotation magnetometer using externally triggered pulsed diode lasers permits measurement of the dynamic properties of polarized electronic spins in semiconductors. The magnetometer may be operated in either continuous-wave (**CW**) or time-resolved modes. In CW mode, a spin polarization is created in the conduction band electrons of n-type GaAs by use of a circularly polarized CW laser. The change in Faraday rotation as a function of applied magnetic field enables measurement of the spin dephasing time T_2^*. In time-resolved mode,



Pump-probe Faraday magnetometer for measurement of spintronic properties in GaAs. Pulsed laser diodes are used for these measurements instead of mode-locked Ti:sapphire lasers, greatly reducing cost and complexity of the completed instrument.

the dynamics of optically pumped spins can be directly observed at arbitrarily long pump-probe delays with a temporal resolution of 75 picoseconds and a spatial resolution of 25 micrometers. The maximum sensitivity is on the order of a thousand spins.

■ **Large-Angle Magnetization Dynamics Investigated by Vector-Resolved, Magnetization-Induced, Optical Second-Harmonic Generation** — We examined the relationship between nonlinear magnetic response and the change in the Gilbert damping parameter α for patterned and unpatterned thin Permalloy ($Ni_{80}Fe_{20}$) films subjected to pulsed magnetic fields. An improved magnetization-vector-resolved technique based on the second-harmonic magneto-optic Kerr effect (SH-MOKE) was used to measure magnetization dynamics after pulse field excitation. The magnetization excitations were achieved with pulsed fields that were aligned parallel to the hard axis of thin Permalloy films while a DC bias field was applied along the easy axis. At low-bias fields, α is inversely related to the bias field, but there was no significant reduction in the absolute value of the magnetization, as might be expected if there were significant spin-wave generation during the damping process. We discuss the discrepancies between data obtained by ferromagnetic resonance, where spin-wave generation is prevalent, and pulsed field studies, and conclude that fundamental differences between the two techniques for the excitation of the ferromagnetic spin system might explain the different proclivity toward spin-wave generation manifest by these two experimental methods.



Vector-resolved, time-domain SH-MOKE signal for magnetization dynamics in Permalloy measured at low applied bias field H_b at which the damping is significantly enhanced. The data show no substantial evidence of inhomogeneities during the magnetization switching process, demonstrating that spin-wave generation does not explain the enhancement of damping for this particular experimental geometry.

Award

■ NIST Bronze Medal for development of Pulsed Inductive Microwave Magnetometer, 2004 (Tom Silva, Tony Kos, and Pavel Kabos).

Recent Publications

J. P. Nibarger, R. Ewasko, M. Schneider, and T. J. Silva, "Dynamic and Static Magnetic Anisotropy in Thin-Film Cobalt Zirconium Tantalum," *J. Magn. Magn. Mater.*, in press.

M. Schneider, A. Kos, and T. J. Silva, "Finite Coplanar Waveguide Width Effects in Pulsed Inductive Microwave Magnetometry," *Appl. Phys. Lett.* **85**, 254-256 (July 2004).

G. S. D. Beach, T. J. Silva, F. T. Parker, and A. E. Berkowitz, "High-Frequency Characteristics of Metal/Native-Oxide Multilayers," *IEEE Trans. Magn.* **39**, 2669-2671 (September 2003).

J. P. Nibarger, R. Lopusnik, T. J. Silva, and Z. J. Celinski, "Variation of the Effective Magnetization and the Landé *g* Factor with Thickness in Thin Permalloy Films," *Appl. Phys. Lett.* **83**, 93-95 (July 2003).

R. Lopusnik, J. P. Nibarger, T. J. Silva, and Z. J. Celinski, "Different Dynamic and Static Magnetic Anisotropy in Thin Permalloy Films," *Appl. Phys. Lett.* **83**, 96-98 (July 2003).

A. Kos, J. P. Nibarger, R. Lopusnik, T. J. Silva, and Z. J. Celinski, "Cyrogenic Pulsed Inductive Microwave Magnetometer," *J. Appl. Phys.* **93**, 7068-7070 (May 2003).

J. P. Nibarger, R. Lopusnik, T. J. Silva, "Damping as a Function of Pulsed Field Amplitude and Bias Field in Thin Film Permalloy," *Appl. Phys. Lett.* **82**, 2112-2114 (March 2003).

T. J. Silva, M. R. Pufall, and P. Kabos, "Nonlinear Magnetooptic Measurement of Flux Propagation Dynamics in Thin Permalloy Films," *J. Appl. Phys.* **91**, 1066-1073 (March 2003).

A. Kos, T. J. Silva, and P. Kabos, "Pulsed Inductive Microwave Magnetometer," *Rev. Sci. Instrum.* **73**, 3563-3569 (October 2002).

T. J. Silva, P. Kabos, and M. R. Pufall, "Detection of Coherent and Incoherent Spin Dynamics During the Magnetic Switching Process Using Vector-Resolved Nonlinear Magneto-Optics," *Appl. Phys. Lett.* **81**, 2205-2207 (September 2002).

See also Recent Publications under Spin Electronics.

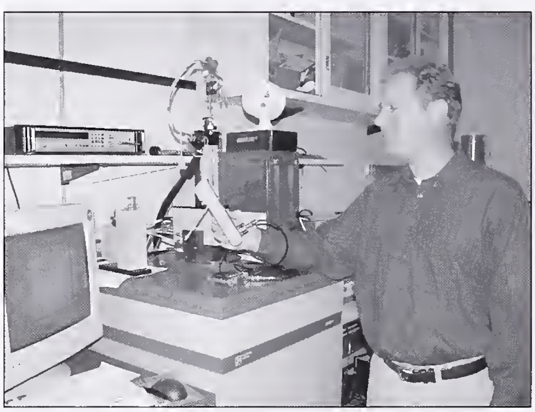
Magnetic Thin Films and Devices

Technical Contact:
Stephen Russek

Staff-Years (FY 2004):
1 professional
1 research associate
3 graduate students

Goals

This project develops measurements and standards for magnetic materials and devices used in the magnetic data storage, magnetoelectronics, and biomedical industries. These measurements and standards assist industry in the development of advanced magnetic recording systems, magnetic solid-state memories, magnetic sensors, magnetic microwave devices, and biomedical materials and imaging systems. Work is focused on novel methods of measuring and studying nanoscale magnetic materials and spin-electronic devices (see section on Spin Electronics). Broadband electrical measurements are being developed to characterize nanoscale devices based on giant magnetoresistance (**GMR**), spin-dependent tunneling (**SDT**), and spin-momentum transfer (**SMT**). New methods are being developed to quantitatively measure the magnetic moment of magnetic thin films, characterize spin transport in magnetic multilayers, and determine the high-frequency properties of nanomagnets. The project is researching magnetic nanostructures, such as molecular nanomagnets, for potential use in nanoscale magnetic data storage, new magnetoelectronic devices, and biomedical imaging.



Brant Cage next to a magnetometer modified to simultaneously measure magnetic moment and high-frequency EPR spectra on nanomagnets.

Customer Needs

The data storage and magnetoelectronics industries are developing smaller and faster technologies that require sub-hundred-nanometer magnetic structures to operate in the gigahertz regime. New types of spintronic devices with increased functionality and performance are being incorporated into data storage and magnetoelectronic technologies. New techniques are required to characterize these magnetic structures on nanometer-size scales and over a wide range of time scales varying from picoseconds to years. For example, the response of an 80-nanometer magnetic device, used in a read head or a magnetic random access memory (**MRAM**) element, may be determined by a 5-nanometer region that is undergoing thermal fluctuations at frequencies of 1 hertz to 10 gigahertz. These fluctuations give rise to noise, non-ideal sensor response, and long-term memory loss. Spintronic devices and nanomagnetic materials are finding applications in other areas such as homeland security and biomedical imaging. These industries require better low-power magnetic field sensors for weapons detection, chemical detection, and magnetocardiograms, and require novel nanomagnetic materials for magnetic-resonance imaging contrast agents and defense applications.

Advances in technology are dependent on the discovery and characterization of new effects such as GMR, SDT, and SMT. Detailed understanding of spin-dependent transport is required to optimize these effects and to discover new phenomena that will lead to new spintronic device concepts. New effects such as SMT and coherent spin transport in semiconductor devices may lead to new classes of devices that will be useful in data storage, computation, and communications applications. Many technologies require or are enabled by the use of magnetic nanostructures such as molecular nanomagnets. The study of magnetic nanostructures will enable data storage on the nanometer scale, a better understanding of the fundamental limits of magnetic data storage, and new biomedical applications.

Technical Strategy

We are developing several new techniques to address the needs of U.S. industries for characterization of magnetic thin films and device structures on nanometer size scales and gigahertz frequencies.

Device Magnetodynamics — We fabricate test structures that allow the characterization of small magnetic devices at frequencies up to 40 gigahertz. The response of submicrometer magnetic devices such as spin valves, magnetic tunnel junctions, and GMR devices with current perpendicular to the plane (**CPP**), are measured in both the linear-response and nonlinear-switching regimes. The linear-response regime is used for magnetic-recording read sensors and high-speed isolators, whereas the switching regime is used for writing or storing data in MRAM devices. We measure the sensors using microwave excitation fields and field pulses with durations down to 100 picoseconds. We compare measured data to numerical simulations of the device dynamics to determine the ability of current theory and modeling to predict the behavior of magnetic devices. We develop new techniques to control and optimize the dynamic response of magnetic devices. These include the engineering of magnetic damping by use of rare-earth doping and precessional switching, which controls switching using the timing of the pulses rather than pulse amplitude. This research is aimed at developing high-frequency magnetic devices for improved recording heads and for imaging of microwave currents in integrated circuits and microwave devices.

Magnetic Noise and Low-Field Magnetic Sensors — We develop new techniques to measure both the low-frequency and high-frequency noise and the effects of thermal fluctuations in small magnetic structures. Understanding the detailed effects of thermal magnetization fluctuations will be critical in determining the fundamental limit to the size of magnetic sensors, magnetic data bits, and MRAM elements. High-frequency noise is measured in our fabricated structures and in commercial read heads. High-frequency noise spectroscopy directly measures the dynamical mode structure in small magnetic devices. The technique can be extended to measure the dynamical modes in structures with dimensions as small as 20 nanometers. The stochastic motion of the magnetization during a thermally activated switching process is measured directly, which will lead to a better understanding of the long-time stability of high-density magnetic memory elements. New methods are being developed to dynamically image thermal fluctuations using time-resolved Lorentz and scanned probe microscopies. These new metrologies will be essential to study and control thermal fluctuations and $1/f$ noise in magnetic and spintronic devices.

***In-Situ* Magnetoconductance and Quantitative Magnetometry** — We develop new techniques to measure the electronic and magnetic properties of magnetic thin-film systems *in situ* (as they are deposited). One such technique, *in-situ* magnetoconductance measurements, can determine the effects of surfaces and interfaces on spin-dependent transport in a clear and unambiguous manner. The effects of submonolayer additions of oxygen, noble metals, and rare earths on GMR are studied. Further, we are developing a new technique to quantitatively measure the moment of magnetic thin films, whose moments are typically on the order of 100 nanojoules per tesla. This quantitative magnetometer will provide measurements that are traceable to fundamental International System (**SI**) quantities.

Nanomagnetism — We are developing new methods to characterize the magnetic properties of nanomagnetic structures such as molecular nanomagnets. One method is high-frequency electron paramagnetic resonance (**EPR**), based on a superconducting quantum interference device (**SQUID**) magnetometer, which can simultaneously measure low-frequency magnetic properties and high-frequency characteristics, such as resonant absorption/emission of microwaves in the frequency range of 95 to 141 gigahertz over a temperature range of 1.8 to 400 kelvins. Molecular nanomagnets, which are the smallest well defined magnetic structures that have been fabricated, exhibit quantum and thermal fluctuation effects that will necessarily be encountered as magnetic structures shrink into the nanometer regime. These systems, which contain from 3 to 12 transition-metal atoms, form small magnets with Curie temperatures of 1 to 30 kelvins. We are investigating new methods of manipulating these nanomagnets by varying the ligand structure and binding them to various films. We are looking at new applications by incorporating the nanomagnets into molecular devices and exploring how the nanomagnets relax nuclear spins in biological systems.

Accomplishments

- **Magnetoresistive Scanning System Implemented** — We built a high-frequency magnetoresistive (**MR**) scanning system to probe high-frequency electric and magnetic fields above high-speed circuits. The system can use either commercial recording heads or NIST-fabricated high-frequency MR sensors. The spatial resolution can be as small as 100 nanometers depending on the type of probe. The system has two 40 gigahertz microwave probes to energize the circuit, and the through power can be monitored simultaneously with the field mapping to determine the invasiveness of the high-frequency probing. A special set of high-frequency structures — which included co-planar waveguide tapers, shorts, and opens — were fabricated to allow imaging of structures that had spatially varying microwave fields in three dimensions. The structures were imaged in three modes: low-frequency magnetic fields (1 kilohertz), high-frequency electric fields (1 to 4 gigahertz), and high-frequency magnetic fields (1 to 4 gigahertz).

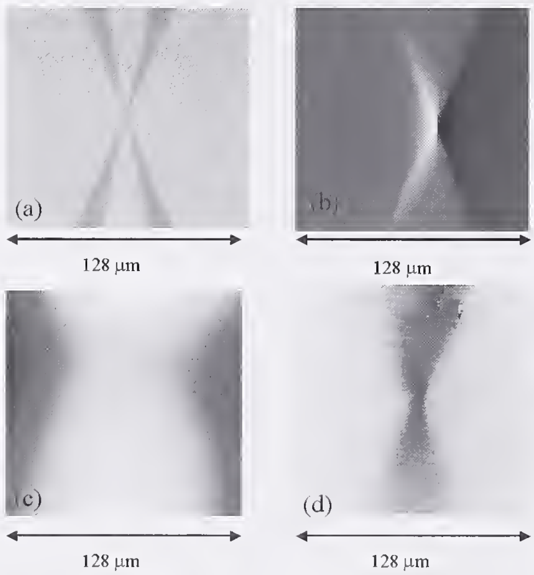
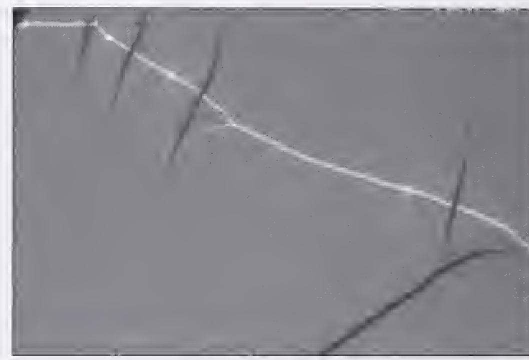


Image of fields above a coplanar waveguide obtained using a high-bandwidth spin-valve recording head: (a) optical image, (b) low-frequency magnetic image, (c) 1 gigahertz capacitive image, (d) 1 gigahertz magnetic image.

■ **Low-Frequency Noise Measurements on Commercial Magnetoresistive Magnetic Field Sensors** — Low-frequency noise was measured in the frequency range from 0.1 hertz to 10 kilohertz on a variety of commercially available magnetic sensors. The types of sensors investigated include those implemented with anisotropic magnetoresistance (**AMR**), giant magnetoresistance (**GMR**), and tunnel magnetoresistance (**TMR**) effect devices. The $1/f$ noise components of electronic and magnetic origin were identified by measuring sensor noise and sensitivity at various applied magnetic fields. For the GMR sensors, both electronic and magnetic components contribute to the overall sensor noise. Maximum noise occurs at the bias field that gives maximum sensitivity. The noise of TMR-based sensors is primarily due to resistance fluctuations in the tunnel barrier, having little to no field dependence. The best low-field detectivity of the sensors that has been measured is on the order of 100 picotesla per root-hertz at 1 hertz. These magnetic sensor noise data are part of a database of low-field sensor performance.

■ **Domain-Wall Pinning by Nanoscale Defects in Amorphous Magnetic Thin Films Using Lorentz Microscopy** — We worked with the Materials Science and Engineering Laboratory on the development of a dynamic Lorentz electron-microscope imaging facility. High-resolution Lorentz images were obtained using a new 200 kilo-electron-volt transmission electron microscope (**TEM**). The TEM was outfitted with a high-resolution camera capable of recording images at 15 frames per second. Magnetic domain-wall motion in soft magnetic thin films was observed in response to a varying in-plane magnetic field. Domain walls became trapped at nanoscale defects and were then studied using standard TEM imaging. Several different types of films were studied, including Ni-Fe alloys, Ni-Fe-Co-Si-B amorphous films, and Co-Fe-B amorphous films.

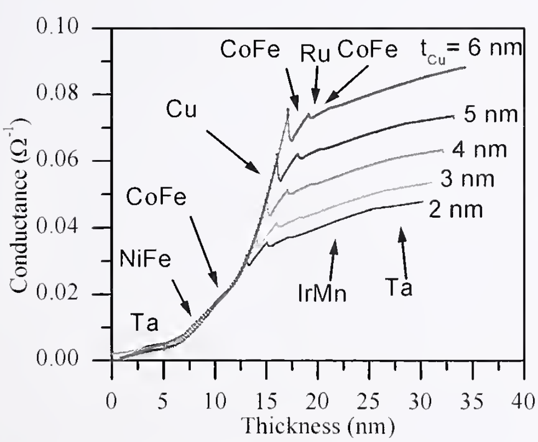


Lorentz microscope image of cross-tie walls and Bloch lines in an amorphous Co-Fe-B-Si magnetic thin film.

■ **Lorentz Imaging of Magnetic Structures** — We successfully fabricated and imaged arrays of magnetic elements using Lorentz microscopy. The arrays consist of elements of different designs that are being considered for magnetic sensor devices. The domain patterns are generally in good agreement with those predicted by micromagnetic simulations. Particular areas near domain walls in some of the elements show indications of fluctuations in the magnetization and are potential sources of noise in the elements.

■ ***In-Situ* Observation of Nano-Oxide Formation in Magnetic Thin Films** — *In-situ* conductance and reflection high-energy electron diffraction (**RHEED**) measurements were taken during the oxidation of 20-nanometer-thick Co and Co-Fe layers. The conductance shows an initial drop with exposure to oxygen followed by a period of increasing conductance. This increase in conductance clearly indicates an increase in specular reflection of electrons at the oxide interfaces. The amount by which conductance increased varied with deposition conditions. The sample with the highest increase in conductance showed an increase in specularity of at least 0.05. RHEED measurements show a blurring of the (111) face-centered-cubic (**FCC**) texture with exposure to oxygen, indicating the formation of an amorphous oxide during the initial conductance drop and conductance increase. After the conductance begins to decrease again, a new diffraction pattern appears in the RHEED data, indicating the formation of CoO with a FCC (111) texture but with a different lattice spacing. These studies shed light on the physical mechanisms for the giant magnetoresistive effect used in magnetic sensors.

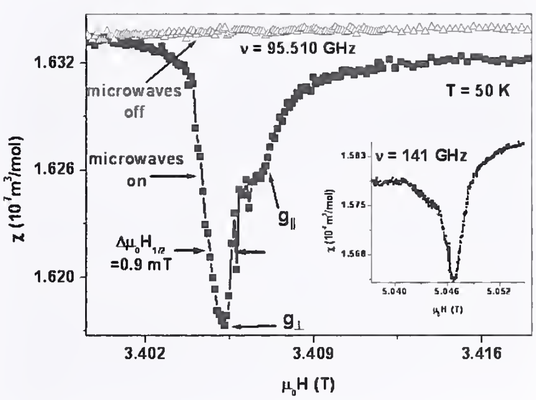
■ **Current Density Distribution in a Spin Valve Determined through *In-Situ* Conductance Measurements** — The sheet conductances of top-pinned spin valves and single-material films were measured *in situ* as the thin-film layers were grown. The data were fit to a Boltzmann transport calculation. The electrical conductivity and electron mean free paths were determined for each material by measuring the *in-situ* conductance of thick, single-material films. The electron transmission probabilities were deduced for each interface from the theoretical fits to the multilayer data. From these interfacial transport parameters the ratio of current density to electronic field, or effective conductivity, was calculated as a function of position for the completed spin valve. The distribution of current in the spin valve was not very sensitive to the overall amount of diffuse scattering at the interfaces. Spin valves are used in modern magnetoresistive read heads in disk drives.



In-situ conductance measurements of a spin-valve taken during growth. The data can be fit to determine the local current density.

■ **Broadband SQUID-Detected Electron Paramagnetic Resonance Probe** — High-frequency electron paramagnetic resonance (**HF-EPR**) is a powerful technique for the characterization of magnetic materials. Measurements at 100 gigahertz and above allow greater resolution in the determination of magnetic energy levels, which are useful for the development of new materials for nanomagnetic data storage, spin electronics, and biomagnetism. However, a serious shortcoming of conventional HF-EPR is its inability to quantitatively measure magnetic moment. We have developed a new technique to make quantitative measurements using a commercial SQUID magnetometer.

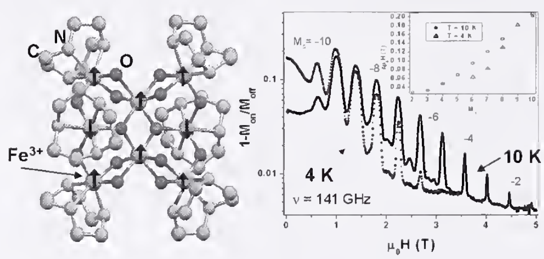
We are able to directly measure the change in magnetic moment of a specimen as microwave stimulation causes resonance at different values of applied magnetic field. The apparatus uses a 95 or 141 gigahertz klystron microwave source followed by an isolator, an attenuator for saturation studies, and a directional coupler. A detector/mixer monitors the frequency and both reflected and incident power. A square-to-round waveguide transition to thin-wall tubing is used to deliver the microwaves to a sample located inside the magnetometer. The probe assembly and sample are mechanically oscillated through the SQUID pick-up loops to obtain the magnetic moment. Quantitative measurement of the degree of saturation at any value of magnetic field allows spin-lattice relaxation times to be calculated in the low-power, saturation



Measurements of molar susceptibility of the EPR standard DPPH using SQUID HF-EPR. The open triangles, for no applied microwaves, show the expected constant value of susceptibility as a function of magnetic field. Upon microwave irradiation at 95.510 gigahertz, a minimum and a small shoulder in susceptibility appear at specific magnetic fields (blue squares). This structure is due to g-tensor anisotropy, which gives rise to two resonance peaks. This splitting cannot be resolved using low-frequency EPR. The inset shows the corresponding susceptibility as a function of swept field at 141 gigahertz, demonstrating a resolution of 1.8 milliteslas in an applied field of 5.0460 teslas.

regime. (Conventional EPR studies require approaching or exceeding the high-power, nonlinear regime.) This is important at high frequencies where the available microwave power is usually limited.

■ **Characterization of Energy Levels and Saturation in Fe-8 Molecular Nanomagnets Using SQUID HF-EPR** — We completed a study of Fe-8 molecular nanomagnets using SQUID HF-EPR. This work is the first to quantitatively measure the magnetization suppression of molecular nanomagnets under microwave illumination. By resonantly pumping low lying energy levels at 95 gigahertz it was possible to suppress the magnetization by 80 percent, indicating the presence of an efficient "spin cascade" that allows energy to be efficiently transported from the low-lying spin levels to high-energy levels. The exact mechanism of this spin cascade is still under investigation.



Structure of Fe-8 molecular nanomagnets and SQUID high-frequency EPR spectra of Fe-8 showing resonant absorption corresponding to transitions between the quantized energy levels.

Recent Publications

N. Stutzke, S. E. Russek, D. P. Pappas, and M. Tondra, "Low-Frequency Noise Measurements on Commercial Magnetoresistive Magnetic Field Sensors," *J. Appl. Phys.*, in press.

B. Cage and S. E. Russek, "Design for a Multifrequency High Magnetic Field Superconducting Quantum Interference Device-Detected Quantitative Electron Paramagnetic Resonance Probe: Spin-Lattice Relaxation of Cupric Sulfate Pentahydrate ($CuSO_4{\cdot}5H_2O$), *Rev. Sci. Instrum.* **75**, 4401-4405 (November 2004).

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A. McCallum and S. E. Russek, "Current Density Distribution in a Spin Valve Determined Through *In Situ* Conductance Measurements," *Appl. Phys. Lett.* **84**, 3340-3342 (April 2004).

A. Saha, S. R. Shah, R. Raj, and S. E. Russek, "Polymer-Derived SiCN Composites with Magnetic Properties," *J. Mater. Res.* **18**, 2549-2551 (November 2003).

N. A. Stutzke, S. L. Burkett, and S. E. Russek, "High-Frequency Noise Measurements in Spin-Valve Devices," *J. Vac. Sci. Technol. B* **21**, 1167-1171 (July 2003).

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S. E. Russek, S. F. Kaka, R. D. McMichael, and M. J. Donahue, "High Speed Switching and Rotational Dynamics in Small Magnetic Thin Film Devices," in *Spin Dynamics in Confined Magnetic Structures II,* Springer-Verlag, Berlin, *Topics Appl. Phys.* **87**, 93-156 (March 2003).

See also Recent Publications under Spin Electronics.

Spin Electronics

Technical Contacts:
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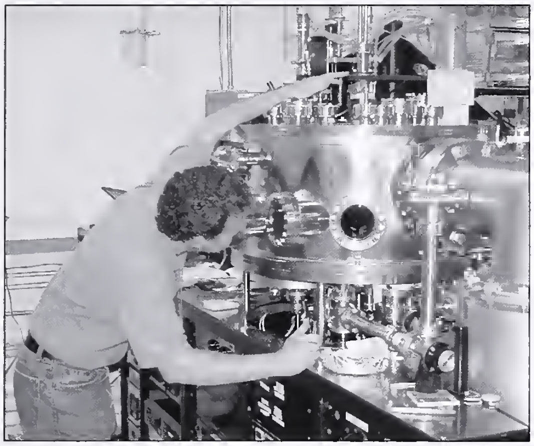
Tom Silva
Stephen Russek

Staff-Years (FY 2004):
2 professionals
2 research associates

Goals

The Spin Electronics Program is creating the foundations for the development of new magnetoelectronic technologies that utilize the electron spin instead of its charge. It investigates the transfer of spin angular momentum from electrons to magnetic thin films to induce magnetization dynamics for applications as microwave oscillators in high-speed signal processing and switching of discrete memory elements.



Bill Rippard depositing magnetic multilayers.

Customer Needs

Wireless communications devices are ubiquitous, ranging from simple radios to more complex structures such as cell phones and wireless Internet systems. All these devices are based upon the transmission and reception of electromagnetic signals, with higher frequencies being required for high data-transmission rates. Common oscillators for wireless applications operate in the gigahertz regime but are large (several millimeters on a side) and must be added onto semiconductor chips after their manufacture, increasing component cost. Further, magnetic data storage technologies require novel methods of high-speed operation of nanoscale memory elements. Traditional magnetic recording and magnetic random access memory (**MRAM**) technologies are encountering problems as they seek to push dimensions below 50 nanometers and speeds above 1 gigahertz.

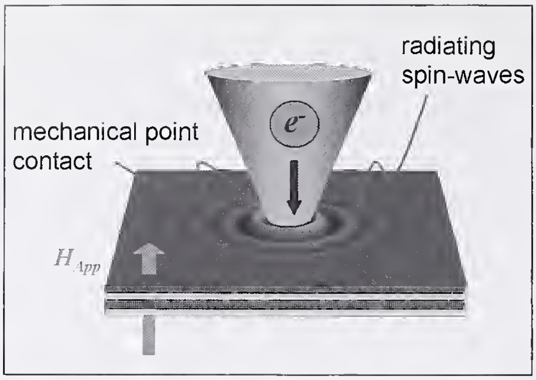
This project concentrates on spin-momentum transfer (**SMT**) from electron currents to multilayer, ferromagnetic films. SMT is a newly discovered phenomenon that appears in nanometer-scale magnetic devices. We are studying metallic devices that use SMT to induce coherent magnetic precession. The precession frequency can be tuned from 1 gigahertz to more than 40 gigahertz by changing the current amplitude, polarization angle, or magnetic field angle. Spin-polarized currents can also be used to switch small magnetic elements used in nanoscale magnetic recording and MRAM technologies. These new techniques may enable more efficient switching of sub-50-nanometer structures at speeds above 5 gigahertz with considerably less power and better selectivity.

Technical Strategy

We are using electron-beam-lithographed point contacts and nanopillar structures to achieve the high current densities needed to induce magnetic excitations in multilayer films. For sufficiently high current densities and applied magnetic fields, there is an abrupt increase in the resistance of a point-contact junction. The resistance step is attributed to the generation of magnons (spin waves) by the SMT effect. We have found that SMT is a generic effect occurring for a wide range of experimental conditions: for both in-plane and out-of-plane fields, for multilayers grown at the both the first and second maxima in "giant magnetoresistance" (GMR), and for ferromagnetically coupled multilayers. We have discovered that SMT occurs in a number of different and previously unexplored alloys of Co, Fe and Ni.

The origin of the SMT effect is conservation of angular momentum. When current flow is perpendicular to the plane (CPP) of a GMR "spin-valve" device, electrons are spin-polarized by the "reference" magnetic layer. Inelastic electron scattering then leads to the transfer of spin angular momentum to the "sense" magnetic layer.

Passing a DC current through magnetic nanostructures can result in oscillations ranging from a few gigahertz to more than 40 gigahertz, the same range used for wireless applications. These new devices are only 40 nanometers in diameter and compatible with standard semiconductor processing, making the new technology attractive for applications. Work is now focusing on developing tunable oscillators and on investigating the fundamental mechanisms that govern the interaction between magnetization and spin current.



Sketch of spin-momentum transfer with mechanical point contacts.

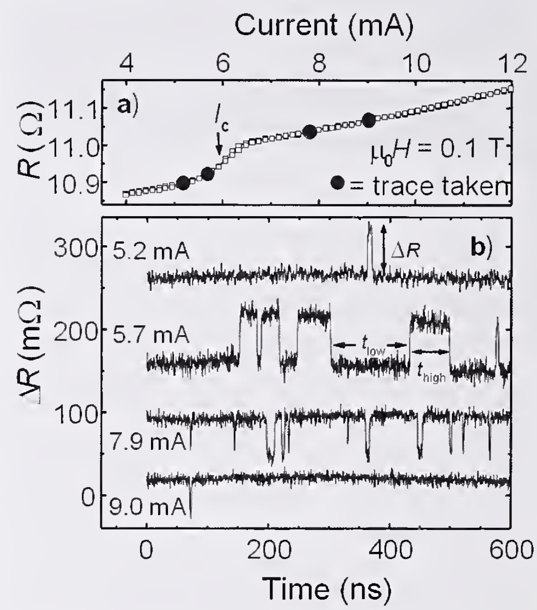
Accomplishments

■ **Tunable Coherent Spin Waves Generated by Direct Current** — We have successfully excited high-frequency magnetic oscillations in a magnetic multilayer structure with a direct current. The oscillations are caused by the torque exerted on the magnetization by the electron spins in the current. The current is injected at high density through a 40 nanometer contact into the magnetic multilayer. At a certain critical value, the current induces precessional oscillations in one of the two magnetic film layers.

These oscillations, detected as a voltage change due to the GMR effect, range in frequency from 6 to 40 gigahertz, with spectral widths as small as 2 megahertz. The small widths imply that the oscillations have lower damping and greater coherence than most known magnetic excitations. The frequency of the oscillations increases with an externally applied magnetic field. For in-plane fields, frequencies as high as 40 gigahertz were obtained. An increase in current causes the oscillation frequency to decrease, with a tunable range of 1 to 5 gigahertz.

■ **Telegraph Switching Induced by Spin-Momentum Transfer** — We demonstrated that a high-density spin-polarized direct current passing through a small magnetic element induces classic two-state random telegraph switching of the magnetization via the SMT effect. The magnetization undergoes large, 40 to 90 degree angular rotations between two states at rates up to 2 gigahertz for a wide range of currents and applied magnetic fields. The switching involves the collective motion of a large number of spins. Such a collective, dynamic source for random telegraph noise is substantially different from that those found in superconducting devices and semiconductor circuitry, where isolated atomic-level defects are usually responsible for two-state fluctuations. The dependence of the switching rates on field and current indicate that device heating alone cannot explain the dynamics. The switching rate also approaches a stochastic regime at sufficiently large currents, where the dynamics are governed by both precession and thermal perturbations.

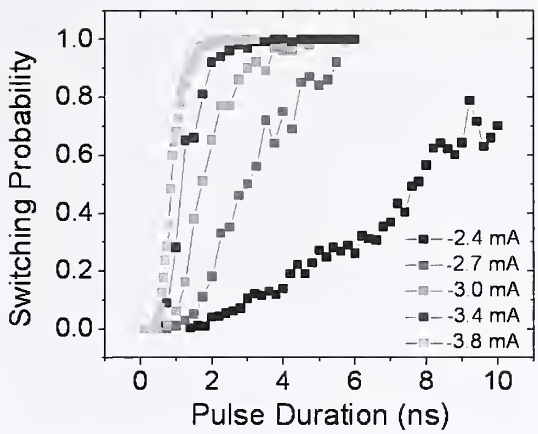
Previous studies have discovered that SMT can cause both irreversible switching and continuous precession in the sense layer of a GMR device. Both of these effects have potential for practical applications in data storage and telecommunications. However, random telegraph noise is a sign that not all SMT-based phenomena are advantageous. Such a noise source could pose a serious problem for the data storage industry as CPP technology is implemented in future sub-150-nanometer size read heads in disk drives. For example, because the noise persists even in large applied fields of 0.5 to 1 tesla, conventional biasing schemes may not stabilize these sensors.



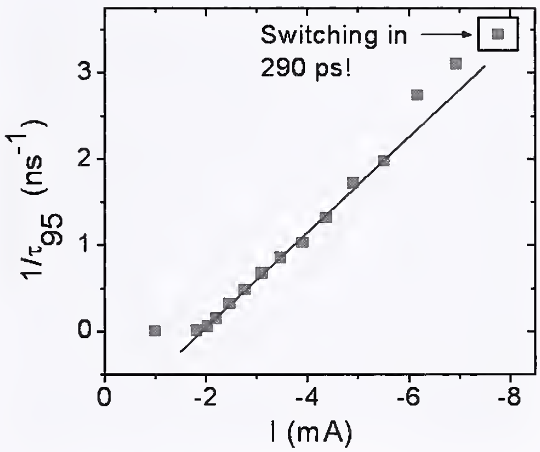
Random telegraph switching induced by spin momentum transfer. Variation in resistance was measured at four values of current.

■ **Spin-Transfer Switching of Magnetic Devices Using Pulsed Currents** —SMT utilizes angular-momentum conservation and spin-dependent transport to manipulate the magnetic state of a device. As a result of SMT, an electrical current can reverse the magnetization orientation. These effects have potential applications in writing data in magnetic random-access memory (**MRAM**) and magnetic hard disk drives. In collaboration with Hitachi Global Storage Technologies, San Jose, California, we have demonstrated magnetization reversal in 100-nanometer-sized magnetic thin-film devices with ultrashort spin pulses. The devices have two magnetic layers separated by a nonmagnetic spacer layer. One of the magnetic layers, the "fixed" layer, is deposited on an antiferromagnet, which pins the magnetization in one direction. The magnetization of the other layer, the "free" layer, is free to rotate. The devices have two stable states: parallel and antiparallel alignment of the magnetizations of the free and fixed layers. The state can be read by using the GMR effect, which causes the antiparallel orientation to have a higher resistance than the parallel orientation. When a current pulse is applied to the device, the electron spins are polarized by the fixed layer, and they transport this angular momentum to the free layer, thereby applying a torque to the free layer and potentially causing reversal of the free-layer magnetization.

We studied rapid reversal due to current pulses whose durations ranged between 100 picoseconds and 100 nanoseconds. The pulse duration required for consistent reversal decreased with increasing current amplitude; for the highest currents applied, reversal occurred in less than 300 picoseconds. This is the shortest reversal time reported yet for SMT-based switching. Such a result is promising for applying SMT as a method of writing magnetic data in MRAM and magnetic hard disk drives, which will be required to operate at gigahertz rates in the near future. By studying the reversal probability over a range of pulse durations and pulse amplitudes, we determined the crossover between thermally activated reversal and a fully dynamic reversal mechanism. In addition, conditions exist for finite switching probability less than unity over a large range of pulse duration, even in the dynamic reversal regime. Such behavior indicates the presence of large room-temperature thermal fluctuations in these magnetic nanostructures, which may represent a fundamental limitation to nanoscale magnetic data storage.



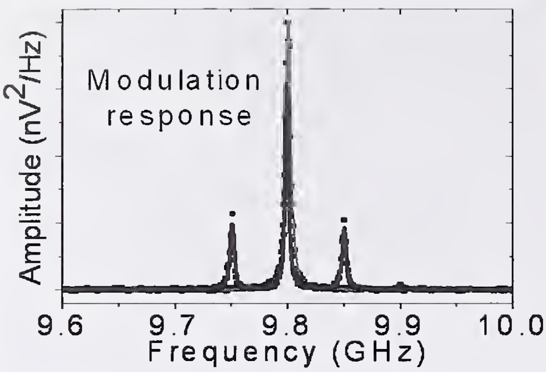
Switching probability vs. pulse duration for several current pulse amplitudes. As the current is decreased, larger pulse durations are required for consistent switching.



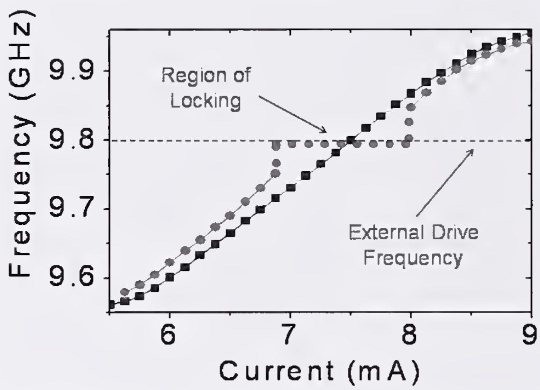
Reciprocal of the pulse duration required for consistent reversal vs. current amplitude. The deviation from linear behavior at low currents indicates thermally activated reversal.

■ **Frequency Modulation and Phase Locking in Spin-Transfer Microwave Oscillators** — Initial work on SMT focused only on the continuous-wave output of the new devices. However, such pure tones transmit no information. Instead, the outputs must be modulated, for instance in amplitude (AM) or frequency (FM), in order to transmit data. We are now able to modulate the current passed through the device. As the current is modulated at frequencies much less than the natural oscillation frequency set by the device, sideband lobes appear on both sides of the original carrier frequency. The details of the outputs can be understood in terms of standard communications theory.

The devices can also be "injection-locked" to an external drive signal close to their natural oscillation frequencies. In this scenario, the devices are forced to oscillate at the same frequency as the injected signal. Over this locking region the relative phases of the two signals can be controlled by the amplitude of the current passed through the device. We are investigating the locking and phase-shifting architectures for possible directional micro-wireless communications and synchronization schemes.



Output of the device with DC current injection only (single peak at 9.8 GHz); device output with additional modulation included at 50 megahertz and amplitude of 400 microamperes (peak at 9.8 GHz with satellites at 9.75 and 9.85 GHz).



Output frequency with no external modulation (squares); device output frequency with presence of an external drive at 9.8 gigahertz (circles).

Recent Publications

M. Pufall, W. Rippard, S. F. Kaka, T. J. Silva, and S. E. Russek, "Frequency Modulation of Spin-Transfer Oscillators," *Appl. Phys. Lett.*, in press.

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W. Rippard, M. Pufall, and T. J. Silva, "Quantitative Studies of Spin-Momentum-Transfer-Induced Excitations in Co/Cu Multilayer Films Using Point-Contact Spectroscopy," *Appl. Phys. Lett.* **82**, 1260-1262 (February 2003).

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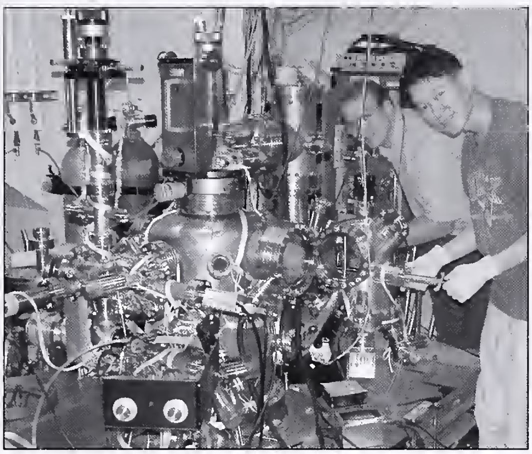
Magnetic Recording Measurements

Goals

This project addresses measurement needs in characterization of magnetic sensors, advanced applications of magnetic sensors, and national security. It is developing magnetoresistive arrays and readout electronics that can image magnetic fields for biomedical research, forensic analysis of magnetic recording media, and current distributions in integrated circuits for nondestructive evaluation. The project develops advanced electron tunneling barriers for superconducting Josephson junctions for future quantum computers.



Robert Owings and Seongshik Oh working on ultra-high-vacuum thin film deposition and analysis system.

Customer Needs

Magnetic Sensors — Magnetoresistive magnetic field sensors have wide application in research and industry. Currently, cryogenic superconducting quantum interference devices are used for the measurement of ultra-low magnetic fields. They provide important information in many areas of basic research, medical magnetic field monitoring, and security. However, it is necessary to develop devices operating at room temperature that are scalable, linear, and have comparable sensitivity to realize the maximum benefit of such devices. The most promising candidates for development are magnetoresistive technologies. Magnetic noise is a critical problem in the development of these devices; such noise can be two orders of magnitude higher than the intrinsic Johnson, shot, and $1/f$ noise of the device. New materials, measurement techniques, and device architectures are required to characterize and reduce the effect of low- and high-frequency magnetic fluctuations.

Magnetic Forensics — In the late 1990s, in a collaboration with the National Telecommunications and Information Administration, we developed basic magnetic imaging technology to retrieve data from damaged or altered magnetic tapes and computer disks by rastering samples with a single sensor to build up an image. We first demonstrated the approach by recovering data from scraps of aircraft "black-box" tape that were too short to be played in a conventional tape deck. For several years, the Federal Bureau of Investigation (FBI) used a prototype of the magnetic imaging system. Because the system was slow, it was used only for testing and special cases. There has been a need for new, faster methods to authenticate magnetic recording tape.

Quantum Computing — Promising candidates for quantum computing devices are quantum bits (qubits) based on Josephson junctions. These junctions are used in magnetic detectors, bolometers, and high-resolution X-ray spectrometers; techniques for their fabrication have been investigated in some detail. However, qubits have far more stringent noise requirements that are now only barely satisfied by current fabrication technology. A significant limitation to the performance of these devices is the generation of defects in the oxide interlayers. The structural origin of these defects is not well established, but is likely a consequence of both the amorphous nature of the oxides and the preparation methods.

Technical Strategy

Magnetic Sensors — In 2004 we embarked on a NIST "Competence" program with the Materials Science and Engineering Laboratory, the Physics Laboratory, and the Information Technology Laboratory on low-noise magnetic sensors. The program includes development of new amorphous and nanocrystalline materials, imaging of magnetic domains, noise measurement in sensor devices, and micromagnetic modeling.

Magnetic Forensics — We are fabricating linear arrays of 64 sensors to scan magnetic recording tape in a single pass. The sensors make use of the magnetoresistance effect, where their electrical resistance changes in response to magnetic fields detected from the tape. Software converts the sensor resistance measurements to visual images that have a resolution of about 60 dots per square centimeter (380 dpi). Linear arrays with 256 microscale

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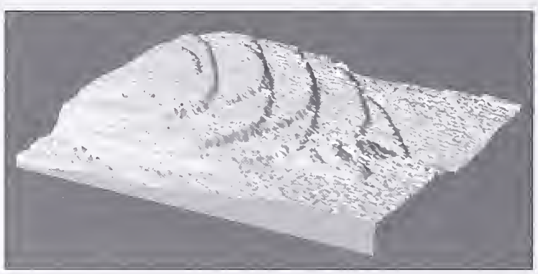
Staff-Years (FY 2004):
1 professional
2 research associates
2 graduate students

sensors are under development to provide ultra-high image resolution of 230 dots per square centimeter (1500 dpi).

Quantum Computing — State-of-the-art Josephson junctions employing superconducting Al or Nb electrodes and native-oxide tunnel barriers typically are fabricated by use of sputter deposition onto thermally oxidized Si wafers for microelectronics fabrication. However, spurious resonant states arising from microstructural defects in the tunnel barrier promote decoherence in Josephson qubits. These resonances may originate from defects and inhomogeneous oxidation during the tunnel barrier formation. Crystalline oxides contain three to four orders of magnitude fewer defects in the frequency range of interest for Josephson qubits. Our capability to prepare and then process samples in ultrahigh vacuum is critical to the development of defect-free, crystalline tunneling barriers. We are now developing a process to grow epitaxial Re on crystalline sapphire (Al_2O_3) substrates.



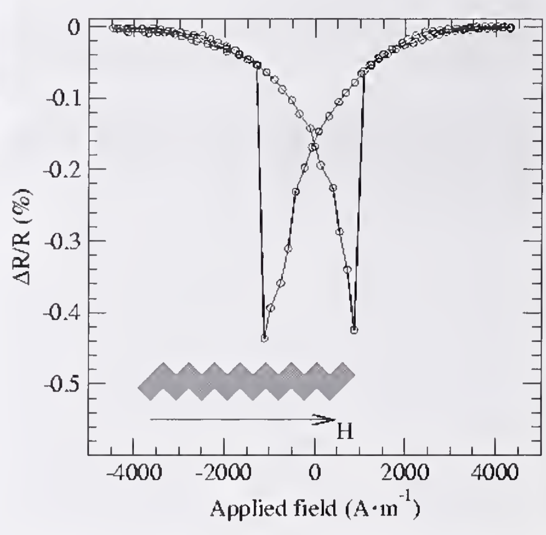
Atomic steps on epitaxial Re grown on sapphire. The lateral dimensions of the image are 0.6 x 0.6 micrometer.

Accomplishments

- **New Zig-Zag Magnetoresistive Field Sensors Developed** — We have developed new "zig-zag" magnetoresistive sensors that, because of their shape, are sensitive to magnetic fields parallel to their axes but insensitive to fields perpendicular. The thin-film devices are also able to distinguish positive and negative fields because their resistance is an odd function of field.

In general, anisotropic magnetoresistive sensors must be biased, with their magnetization at an angle with respect to the current direction. Our new sensors are fabricated in a zig-zag pattern that pins the magnetization at alternating positive and negative 45 degrees to the direction of the current flow. This novel approach provides a built-in magnetization bias determined by the corrugation of the edges. Since the angle of magnetization of the magnetic domains is controlled only by the sensor shape, and not by adjacent biasing fields, the devices may be scaled to nanometric dimensions. When the sensor is exposed to a magnetic field oriented in the direction of the current, the angle of magnetization relative to the current in both sets of the domains decreases. This results in an increase of electrical resistance in each domain and in the entire device. For magnetic fields in the negative current direction, the magnetization angle increases and the resistance decreases. For magnetic fields in the perpendicular axis, the magnetization angle increases in one set of magnetic domains and decreases in the other, resulting in no net change in device resistance.

Micrograph of a zig-zag magnetoresistive element obtained by use of a scanning electron microscope with polarization analysis (SEMPA). With respect to the long axis of the sensor (the axis of current), light gray indicates magnetization at an angle of +45 degrees, dark gray at an angle of –45 degrees. The magnetic domain patterns were also accurately modeled with NIST's Object Oriented MicroMagnetic Framework (OOMMF).



Transfer curves of resistance change versus magnetic field along the axis of a 3-millimeter by 16-millimeter, 30-nanometer-thick, Ni-Fe zig-zag element.

- **Images of Erased Tapes** — We conducted high-resolution magnetic imaging measurements on erased audio tape for the FBI as part of its participation in a study by the National Archives and Records Administration (**NARA**) on the feasibility of recovering audio from an 18.5 minute gap in a tape from the Nixon White House.

NARA's 6-millimeter-wide test tapes had been recorded and then erased in a manner similar to that of the Nixon tapes. As described by NARA, the test tapes were "recorded on an original Nixon White House Sony 800B tape recorder, then erased on Rosemary Woods' UHER 5000." Tests were made of both an erased audio recording and an erased blank section of tape. The FBI could find no trace of the recording or erasure marks using a standard imaging technique with a ferromagnetic fluid. However, the NIST researchers were able to detect an extra noise band on the outside edge of the erased section of the audio tape that was not evident on the erased section of blank tape. The noise band was scanned at high resolution and converted to an audio signal. It consisted of only very low frequency sounds, with no trace of audible speech. In a press release dated May 8, 2003, Archivist of the United States John W. Carlin said, "I am fully satisfied that we have explored all of the avenues to attempt to recover the sound on this tape. The candidates were highly qualified and used the latest technology in their pursuit."

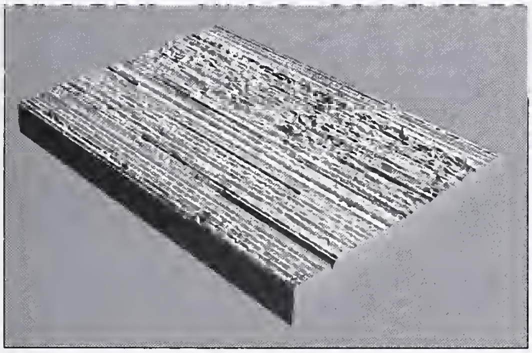
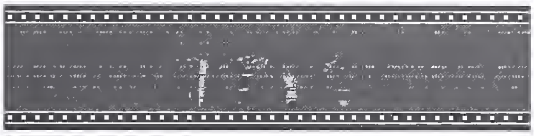


Image of magnetic field from test tape out of the FBI/NARA study. This tape had audio on one side that had been erased. The left side of the tape is relatively smooth, whereas the right side is rough. The extra ridge near the far right of the tape was present only in tapes that had previously been recorded with audio. However, when the signal was converted back to sound, there was no intelligible audio that could be discerned. One second of play time is shown.

■ **New System Sees Crimes on Audiotape** — We developed a real-time magnetic imaging system that enables criminal investigators to see signs of tampering in audiotapes — erasing, over-recording, and other alterations — while listening to the tapes. The new system, which permits faster screening and more accurate audiotape analysis than currently possible, was delivered to the FBI in September 2004 and will be evaluated for possible routine use in criminal investigations.

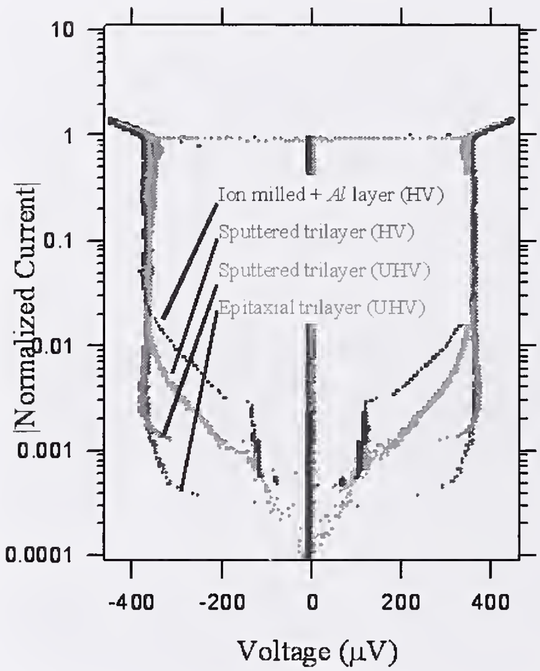
At the heart of the technology is a cassette player modified with an array of 64 customized magnetic sensors that detects and maps the microscopic magnetic fields on audiotapes as they are played. The array is connected to a desktop computer programmed to convert the magnetic data into a displayable image. Authentic, original tapes produce images with non-interrupted, predictable patterns, whereas erase and record functions produce characteristic "smudges" in an image that correlate to "pops" and "thumps" in the audio signal. The original markings specific to different types of tape players are not present on tape copies. An examiner can use this new system to help determine the authenticity of a tape and also help determine whether that tape is a copy. The benefits of the system are its speed in correlating sounds with magnetic marks on tape, and the fact that it makes an image without damaging the tape.



This figure shows approximately one-half second of data that were acquired in real time as the tape passed over the 64-element head. The streaks show where a cassette erase head stopped on the tape.

■ **Improved Superconducting Tunnel Junctions Using Epitaxial Underlayers** — In collaboration with the Quantum Electrical Metrology Division, we studied the growth of tunnel junction base electrodes to investigate the role that crystalline quality plays in device performance. We found that there is a strong correlation between the morphology of oxidized base electrodes and the lowering of subgap currents, and through the use of epitaxial seed layers, junctions with even lower subgap currents were obtained. In order to accomplish this, we engineered Josephson junctions with increasingly improved crystalline quality and were able to correlate the microstructure of the junctions with low-frequency transport measurements. Our data indicate a strong correlation between improved crystallinity of the tunnel barrier and reduced subgap leakage currents.

The evaporated trilayers that showed the best characteristics are grown using a unique method in our ultra-high-vacuum surface-science chamber. We began with clean Si(111) substrates with perfect surface cleanliness. This is confirmed by observing the (7×7) reconstruction of the atoms. We then grew a thin film of Al at low temperature and gently brought it to room temperature. This forms an atomically smooth, epitaxial Al surface upon which we can then prepare the superconducting tunnel junction. The sub-gap conductance was improved by nearly two orders of magnitude as we developed cleaner and better methods, culminating in epitaxial trilayers.



Subgap conductance curves from standard high-vacuum junctions compared to our results as we improved the fabrication conditions. The lowest subgap conductances were obtained with epitaxial Al base electrodes.

Recent Publications

D. P. Pappas, F. da Silva, R. N. Clarke, J. Unguris, W. C. Uhlig, and A. Kos, "Zigzag Shaped Magnetic Sensors," *Appl. Phys. Lett.*, in press.

D. P. Pappas, A. Nazarov, D. Stevenson, S. Voran, M. E. Read, E. M. Gormley, J. Cash, K. Marr, and J. Ryan, "Second Harmonic Magneto-Resistive Imaging to Authenticate and Recover Data from Magnetic Storage Media," *J. Elect. Imag.*, in press.

R. W. Simmonds, K. M. Lang, D. A. Hite, S. Nam, D. P. Pappas, and J. M. Martinis, "Decoherence in Josephson Phase Qubits from Junction Resonators," *Phys. Rev. Lett.* **93**, 077003/1-4 (August 2004).

K. M. Lang, D. A. Hite, R. W. Simmonds, R. McDermott, D. P. Pappas, and J. M. Martinis, "Conducting Atomic Force Microscopy for Nanoscale Tunnel Barrier Characterization," *Rev. Sci. Instrum.* **75**, 2726-2731 (August 2004).

M. G. Pini, A. Rettori, D. P. Pappas, A. V. Anisimov, and A. P. Popov, "Surface Magnetic Canting in a Nonuniform Film," *J. Magn. Magn. Mater.* **272-276**, 1152-1153 (May 2004).

B. L. Zink, K. D. Irwin, G. C. Hilton, D. P. Pappas, J. N. Ullom, and M. E. Huber, "Lithographically Patterned Magnetic Calorimeter X-ray Detectors with Integrated SQUID Readout," *Nucl. Instrum. Methods Phys. Res. A* **520**, 52-55 (March 2004).

D. A. Hite, S. E. Russek, and D. P. Pappas, "*In-Situ* Conductance Characterization of Fe/Ag Multilayer Contacts on GaAs," *J. Appl. Phys.* **94**, 621-625 (July 2003).

A. P. Popov, A. V. Anisimov, and D. P. Pappas, "Mechanisms for the Multistep Spin Reorientation of Ultrathin Fe films on Gd," *Phys. Rev. B* **67**, 094428/1-6 (March 2003).

F. C. da Silva, D. P. Pappas, and C. M. Wang, "Magnetic Thin Film Interlaboratory Comparison," *J. Res. NIST* **108**, 125-134 (March 2003).

Z. Y. Liu, P. A. Dowben, A. P. Popov, and D. P. Pappas, "Consideration of Possible Mass and Velocity Corrections to Magnetic Experiments," *Phys. Rev. A* **67**, 033202/1-6 (January 2003).

W. F. Egelhoff, M. D. Stiles, D. P. Pappas, D. T. Pierce, J. M. Byers, M. B. Johnson, B. T. Jonker, S. F. Alvarado, J. G. Gregg, J. A. C. Bland, and R. A. Buhrman, "Spin Polarization of Injected Electrons," *Science* **296**, 1195a (May 2002).

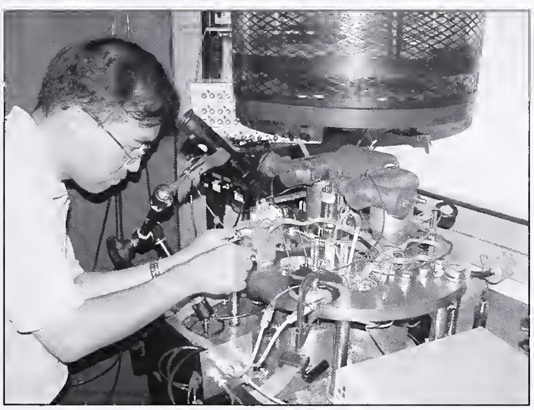
NANOPROBE IMAGING

Technical Contact:
John Moreland

Staff-Years (FY 2004):
1 professional
4 research associates
1 graduate student

GOALS

This project develops micro-electromechanical systems (**MEMS**) for nanomagnetic research. Microcantilever-based applications include scanned-probe microscopy; ultra-sensitive resonance magnetometers with sub-monolayer sensitivity; torsional oscillator magnetometry and ferromagnetic resonance spectroscopy of submicrometer magnetic dots; and scanned probes for measuring microwave power above circuits. Nanoparticle applications include magnetic manipulation and measurement of single molecules and radio-frequency tags for magnetic resonance imaging (**MRI**). Device applications include alkali-metal vapor cells for chip-scale atomic clocks and magnetometers and high-gradient micro-electromagnets, micro-radio-frequency coils, and torsional oscillator sensors for pulsed-field-gradient MRI.



Dong-Hoon Min preparing resonant cantilever for measurement of absolute magnetic moment of a magnetic thin film.

CUSTOMER NEEDS

The Information Storage Industry Consortium's recording-head metrology roadmap calls for high-resolution, quantitative magnetic microscopes and magnetometers that go beyond the limitations of current technology. Magnetic measurement systems have become increasingly complex. Our expertise in magnetism, probe microscopy, and cleanroom microfabrication techniques helps move instruments from the development stage to routine operation in the industrial laboratory and on the factory floor.

In order to improve upon magnetic microscopes, our project is focusing on specialized magnetic-force-microscope (**MFM**) tips for imaging heads and media. New approaches based on magnetic force imaging are being developed to go beyond the current MFM resolution of 10 nanometers. We are developing ways to attach submicrometer magnetic resonance particles to ultra-sensitive cantilevers and to position particles a few nanometers from the sample surface. Instrumentation will also be adapted to a new class of microwave probe stations that use micromachined probe chips to extend voltage and current probe measurements on microwave circuits with submicrometer spatial resolution in the 100 gigahertz range. We are extending this technology to biological and medical applications in an effort to develop applications-specific magnetic particles as well as highly specialized microchips. For example, we are currently developing a chip-scale MRI system for ultra-high-resolution MRI of cell organelles.

The project also develops single-molecule manipulation and measurement (SM^3) techniques. This program will advance single-molecule metrology by developing a novel platform, based on bio-nano-electromechanical systems, that integrates electrical, magnetic, optical and spectroscopic technologies. There is currently a lack of measurement tools and methods for isolating, manipulating and probing the behavior and structure of single molecules. The single-molecule research is a collaboration among divisions in EEEL, the Physics Laboratory, the Chemical Science and Technology Laboratory, and the Information Technology Laboratory.

We are also working with the Physics Laboratory to develop a chip-scale atomic clock (**CSAC**). The most common type of passive frequency standard is the vapor-cell frequency reference. We are exploring microfabrication technologies to answer the question: "What is the smallest size for an atomic clock?" The difficulty associated with the large size of the microwave cavity typical of large clock designs can be overcome by using an all-optical excitation method based on coherent-population-trapping (**CPT**) resonances where a laser pump beam is modulated at the atomic hyperfine frequency, resulting in two optical fields separated by the atomic oscillation frequency. Thus, the fundamental limit to the clock size is the wavelength of the optical radiation, which is of the order of only one micrometer, compared to a few centimeters for a microwave cavity clock design.

Technical Strategy

We are developing new tools for measurements of nanoscale magnetic phenomena and representations of magnetic units for the next generation of data-storage devices. We are developing MEMS magnetometers with integrated magnetic samples that can offer tremendous gains in magnetic-moment sensitivity. Our micromachining facility is at the state of the art, providing the tools necessary for bulk and surface micromachining on Si wafers. Our plans over the next four years are to demonstrate new metrology instrumentation based on MEMS devices that will enable us to create instruments that have superior performance compared to current magnetic-measurement methods.

Micro-Electromechanical Systems Magnetometer Development — Micrometer- and sub-micrometer-scale magnetic measurements have proven to be a challenge for conventional magnetometers, and new methods are being employed to probe magnetism on this scale. Conventional measurements are made on arrays of micromagnetic dots. However, due to fabrication limitations, the results are clouded by statistical variations in dot shape, size and spacing. Thus, more sensitive detectors are needed that can measure magnetic properties of individual dots.

In particular, there is a need to understand atomic-scale spin damping in ferromagnetic systems in order to improve the switching speed of magnetic devices. For example, data-transfer rates for commercial disk drives will soon require operational bandwidths in excess of 1 gigahertz. For switching times less than 1 nanosecond, gyromagnetic effects dominate. One way to understand damping is to investigate size effects as magnetic devices are reduced to submicrometer dimensions. Studies of magnetic nanodots will give a better understanding of spin damping and therefore aid in the development of faster disk drives.

We will provide new magnetometers based on highly specialized MEMS chips fabricated at NIST. The instruments will be inexpensive, since MEMS can be batch-fabricated in large quantities. In addition, large-scale magnetic wafer properties can be transferred to smaller MEMS magnetometers so that nanometer-scale measurements can be calibrated with reference to fundamental units. In particular, our focus will be on developing torque and force magnetometers, magnetic-resonance spectrometers, and magnetic-resonance imaging (MRI) microscopes on MEMS chips. Over the long term, we expect that this technology will lead to atomic-scale magnetic instrumentation for the measurement and visualization of fundamental magnetic phenomena.

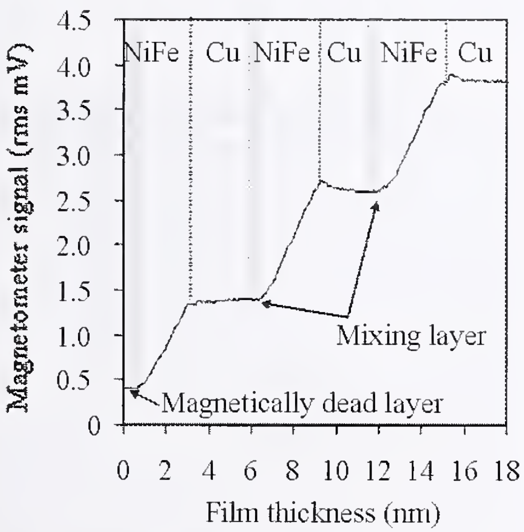
Scanning Probe Development — In order to improve upon scanning probe microscopes, such as MFM, and keep pace with industry needs, we are focusing on specialized MFM tips for imaging heads and media. Ultra-small tips are currently being developed for magnetic-image resolution of 20 nanometers. We are looking at new technologies for fabricating, controlling and measuring nanometer-scale magnetic structures near the probe tip. In particular, MFM resolution can improve only with the development of more sensitive cantilevers for measuring the small magnetic forces associated with nanometer-scale magnetic probe tips. Conventional MFM is not an intrinsically quantitative technique. However, quantitative field mapping can be done with tiny field probes based on mechanical detection of magnetic resonance in the probe. We are developing ways to fabricate small magnetic-resonance particles on ultra-sensitive cantilevers and position the particles a few nanometers from the sample surface for field mapping with one-nanometer resolution.

Single-Molecule Manipulation and Measurement — The semiconductor electronics industry has driven the development of fabrication tools that are capable of patterning structures on the order of 100 nanometers, smaller than cellular dimensions. Using MEMS, we can create three-dimensional structures that are commensurate with the size of biomolecules. Interactions of single molecules with nanoscale mechanical structures, restriction elements, and other single molecules will be probed by electronic, electromechanical and optical techniques. The effort will result in a well characterized SM^3 platform integrated with AFM, fluorescence resonance energy transfer (FRET), optical microscopy, and electronics, thereby enabling a wide variety of single-molecule studies. Determination of DNA structure will be performed by directly interrogating ordered bases as they are threaded through a well characterized nanopore.

Chip-Scale Atomic Clock — The main thrust of the CSAC project is to develop a cesium (Cs) vapor cell with submillimeter dimensions and to study the effect of the vapor cell wall coatings and buffer gases on the intrinsic line width of the Cs atomic transitions. The challenges for developing a microfabricated atomic-clock vapor cell are threefold. First, the process must be performed at the wafer level in order to take advantage of batch fabrication of the cells. Second, the process must provide a means for evacuating and subsequently backfilling the cell with Cs or Rb without the need for microvalve technology or glass tubing connections to the cell. Third, the process must allow for the introduction of cell coatings or buffer gases to minimize size-effect spectral broadening. We are currently investigating several approaches to cell microfabrication based on wafer bonding and bulk and surface micromachining techniques of Si. In addition, we will be investigating schemes that rely on direct magnetic coupling between a mechanical micro-oscillator and the Cs vapor, thus eliminating the need for external feedback control.

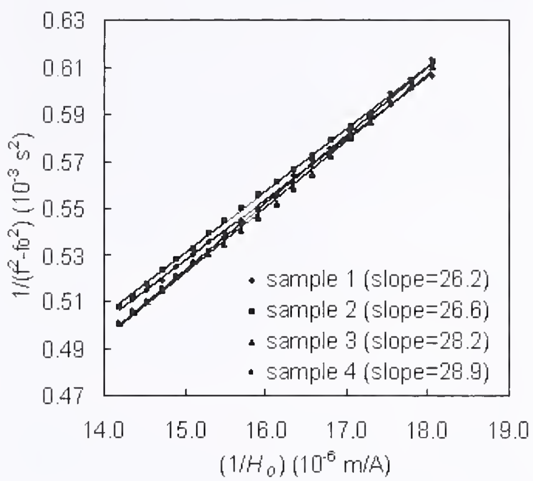
Accomplishments

■ **Frequency Modulation Detection Implemented in MEMS *In-Situ* Magnetometer** — We have improved our *in-situ* magnetometer for monitoring the magnetic properties of thin-film multilayers during deposition. By tracking the frequency shift we can separate the magnetic signal from the mass loading and thermal effects. The demonstrated sensitivity for a Ni-Fe film deposition is less than 0.1 nanometer. This is sufficient for fundamental studies of thin-film interface magnetism and magnetic exchange interactions in multilayer structures.



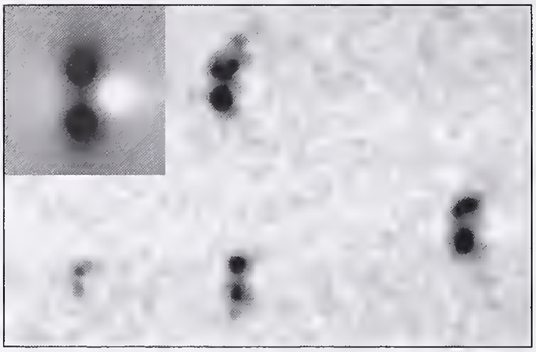
Magnetometer response as a function of film thickness measured with a quartz crystal micro-balance for $Ni_{0.8}Fe_{0.2}$(3 nm)/Cu(3 nm) multilayer film.

■ **Measurements of Absolute Magnetic Moment** — We have demonstrated the concept for an ultra-small magnetic moment standard reference material based on a thin magnetic film deposited onto a cantilever detector. We performed micro-torque magnetometry measurements on a series of cantilevers with thin Permalloy ($Ni_{80}Fe_{20}$) samples deposited onto them. These cantilevers and the Permalloy samples have been optimized for moments on the order of a nano-joule per tesla. The method has promise for relating all critical measurements pertaining to the determination of the magnetic moment to frequency, which can be determined accurately with a frequency source based on an atomic clock.



Plots of reciprocal frequency as a function of reciprocal magnetic field for 4 samples of $Ni_{0.8}Fe_{0.2}$, 500 nanometers thick. The inverse of the slope of the line is proportional to the magnetic moment, and the inverse of the intercepts is proportional to the anisotropy energy. The average values obtained for the samples are respectively 4.67 ± 0.46 nanojoules per tesla and 143.7 ± 6.4 joules per cubic meter.

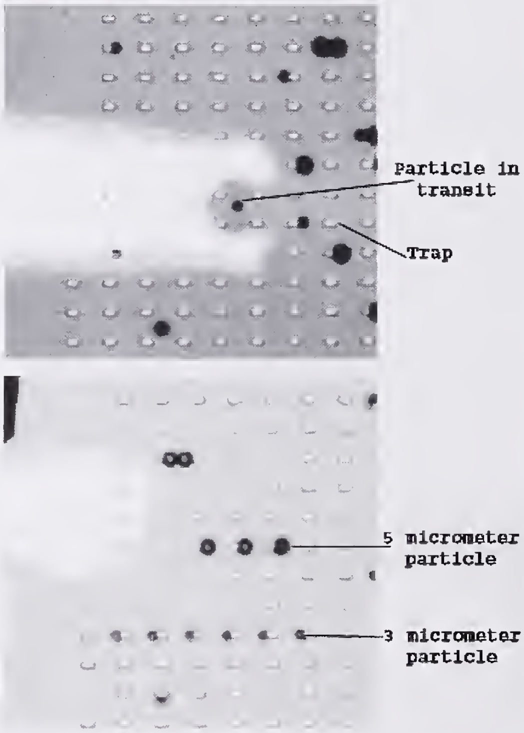
■ **Modeling of MRI images for Single Particle RF Tag Applications** — We developed a computer program for calculating the static field profile near microscopic magnetic particles with different magnetic moments. The program is based on solving Maxwell's equations with given boundary conditions. The program also predicts the effect of the field profile on MRI images for different imaging scenarios (phase versus frequency encoding). The program goes beyond previous calculations to include the limit below one volume pixel (**voxel**). Typical mimimum voxel sizes for MRI instruments are around 300 micrometers. However, even if a magnetic particle is much smaller then a voxel, as is the case for micrometer-sized particles, its influence on the applied magnetic field locally can be significant several voxels away due to the narrow line width of the proton nuclear magnetic resonance of water. By developing particles with specific shapes and sizes and materials with nanometer dimensional control, very distinct changes in the MRI image will occur and can be detected with research-grade MRI systems used in medical centers today. The particles would be used as tags for individual cells in the body to monitor *in-vivo* cell functionality.



MRI image distortion due to the presence on individual magnetic polystyrene spheres about 1 micrometer in diameter. The data were taken at the Laboratory of Functional and Molecular Imaging at the National Institute of Health (NIH) and modeled at NIST (see inset).

■ **High-Throughput Lab-on-Chip for Sorting Biologically-Compatible Magnetic Particles** — We have integrated a novel microfluidic magnetic trap platform with an external magnetic force microscope (**MFM**) to capture and sort magnetic particles into discrete positions in an array. The principle of the platform is to sequentially flow magnetically modified biological samples into the array and to sort them to produce a matrix reference. The matrix can then be transported to a location where each individual magnetic particle — and hence biological sample — can be probed to obtain details about its medical or forensic functions, such as gene sequence or physical structure in different physiological environments. Alternatively, the array can be used to sort particles of varying sizes and magnetic susceptibilities, thereby providing standards for magnetic particles used in medical applications such as contrast enhancers in magnetic resonance imaging or to coax together severed nerve cells so that they can repair themselves and restore mobility to limbs.

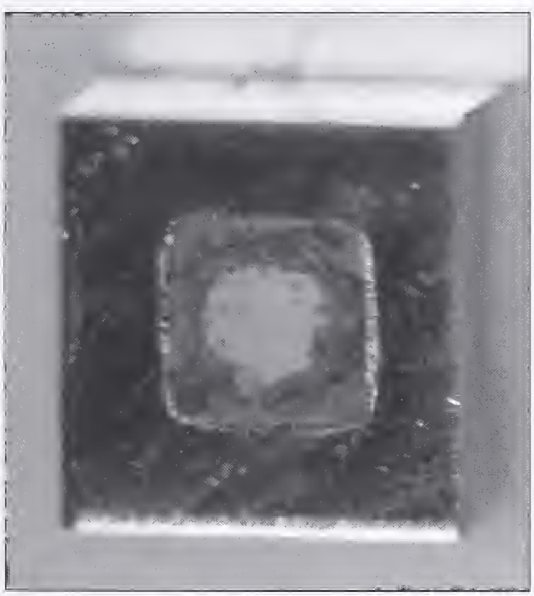
The platform consists of an array of magnetic trapping elements separated from the fluid sample by an optically transparent thin membrane. The magnetic particles are trapped by the local field gradients produced by the magnetic element with a force of approximately 100 piconewtons, which can ensure that the particle remains in the desired position through rigorous transport. The cobalt-coated MFM cantilever serves as a magnetorobotic arm that provides a translatable local magnetic field gradient that captures and moves the particles with nanometer precision. We integrated the electronics of the magnetorobotic arm with a digital camera and programmed it to sort an initially random distribution of particles by moving them within the array of magnetic trapping elements. The forces acting on a 1 micrometer diameter particle were measured by viscous drag in the fluid to be on the order of 50 piconewtons, thereby allowing a sorting rate of approximately 1200 particles per minute. Release of the particles from the cantilever is achieved by retracting the arm, leaving the particles in the solution, retained by the transparent membrane.



An array of traps (1 micrometer × 3 micrometer rectangles) and randomly distributed magnetic particles (3 micrometer and 5 micrometer diameters). The white area is the magnetorobotic arm. The top image is before sorting and the bottom is after sorting.

■ **Atomic Vapor Cells for Chip-Scale Atomic Clocks** — In collaboration with colleagues from the Physics Laboratory, we successfully microfabricated a cesium (Cs) vapor cell using Si micromachining techniques. Additionally, we developed vapor-cell filling techniques and measured the effect of vapor-cell buffer-gas pressure on the intrinsic line width of Cs vapor atomic transitions. The cells have volumes just under 10 cubic millimeters, with spectral line widths less than 1 kilohertz for a 9.2 gigahertz Cs hyperfine absorption line. Other cells fabricated at NIST using the same process, and with volumes as small as 1 cubic millimeter, have line widths only slightly larger. Miniaturized atomic clocks (volume less than 1 cubic centimeter) have military and civilian applications, including synchronization of encryption keys and communication networks and to help prevent jamming of global positioning systems. In addition to a high level of miniaturization, other advantages include lower cost, higher reproducibility, and integration with control electronics and sensors.

Novel excitation techniques have been investigated by the Physics Laboratory, including coherent population trapping (**CPT**) resonances in which two optical fields are applied to a Cs vapor cell. The two fields are obtained by modulating the drive current for a vertical-cavity surface-emitting laser (**VCSEL**), thus generating laser sidebands separated by about 9.2 gigahertz. This eliminates the need for a resonating cavity and permits the cell size to be made smaller than the wavelength of the microwave radiation. At a critical frequency difference between the two laser frequencies, a dark-line or CPT resonance occurs, signified by a decrease in the Cs vapor optical absorption. This resonance is then used to lock the modulation frequency of the laser. The advantage of using the CPT method over conventional microwave excitation is that the clock can be made much smaller and simpler. Eventually, the goal is to develop a clock physics package (including laser, laser optics, vapor cell, vapor cell heater, photodetector, and magnetic shield) based on the CPT scheme with a volume less than 3 cubic millimeters.



Micromachined cesium vapor cell, about 1.2 millimeter square.

We developed two methods for filling and sealing the micromachined cells: (1) chemical reaction between barium azide and cesium chloride in an ultra-high vacuum system followed by anodic bonding of the Si chip to a glass window in a nitrogen buffer gas ambient, and (2) direct injection of liquid Cs in an anaerobic chamber followed by anodic bonding to a glass window in a nitrogen buffer gas ambient. In principle, both processes are scalable to wafer level production.

Recent Publications

P. D. D. Schwindt, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, "A Chip-Scale Atomic Magnetometer," *Appl. Phys. Lett.,* in press.

D. Min, A. McCallum, S. E. Russek, and J. Moreland, "Sub-Monolayer *In-Situ* Micromechanical Torque Magnetometer with Integrated Fiber Optic Interferometer for UHV Applications," *J. Magn. Magn. Mater.,* in press.

T. M. Wallis, J. Moreland, B. F. Riddle, and P. Kabos, "Microwave Power Imaging with Ferromagnetic Calorimeter Probes on Bimaterial Cantilevers," *J. Magn. Magn. Mater.,* in press.

S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, "A Microfabricated Atomic Clock," *Appl. Phys. Lett.* **85**, 1460-1462 (August 2004).

L. Gao, D. Q. Feng, L. Yuan, T. Yokota, R. Sabirianov, S. H. Liou, M. Chabot, D. Porpora, and J. Moreland, "A Study of Magnetic Interactions of $Ni_{80}Fe_{20}$ Arrays Using Ultra-Sensitive Microcantilever Torque Magnetometry," *J. Appl. Phys.* **95**, 7010-7012 (June 2004).

L.-A. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg, and J. Kitching, "Microfabricated Alkali Atom Vapor Cells," *Appl. Phys. Lett.* **84**, 2694-2696 (April 2004).

E. Mirowski, J. Moreland, S. E. Russek, and M. J. Donahue, "Integrated Microfluidic Isolation Platform for Magnetic Particle Manipulation in Biological Systems," *Appl. Phys. Lett.* **84**, 1786-1788 (March 2004).

M. D. Chabot and J. Moreland, "Micrometer-Scale Magnetometry of Thin $Ni_{80}Fe_{20}$ Films Using Ultrasensitive Microcantilevers," *J. Appl. Phys.* **93**, 7897-7899 (May 2003).

J. Moreland, "Micromechanical Instruments for Ferromagnetic Measurements," *J. Phys. D: Appl. Phys* **36**, 39-51 (January 2003).

J. Moreland, J. A. Beall, and S. E. Russek, "Resonating Torque Microbalance for *In Situ* Measurements of Ferromagnetic Films," *J. Magn. Magn. Mater.* **242-245**, 1157-1159 (April 2002).

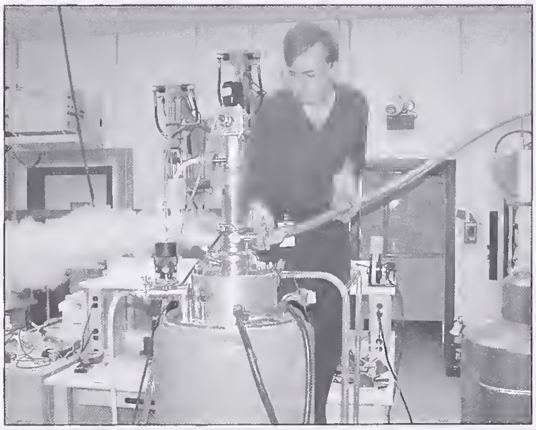
Superconductor Electromagnetic Measurements

Technical Contact:
Jack Ekin

Staff-Years (FY 2004):
1 professional
1 technician
2 research associates

Goals

This project specializes in measurements of the effect of mechanical strain on superconductor properties such as critical-current density for applications in magnetics, power transmission, and electronics. Recent research has produced the first electromechanical data for the new class of high-temperature coated conductors, one of the few new technologies expected to have an impact on the electric-power industry. The Strain Scaling Law, previously developed by the project for predicting the axial-strain response of low-temperature superconductors in high magnetic fields, is now being generalized to three-dimensional stresses, for use in finite-element design of magnet structures, and to high-temperature superconductors. Recent research includes extending the high-magnetic-field limits of electromechanical measurements for development of nuclear-magnetic-resonance (**NMR**) spectrometers operating at 23.5 teslas and 1 gigahertz, and the next generation of accelerators for high-energy physics. The project has diversified its research to include magnetoresistance studies on a new class of carbon nanostructures using our high-field superconducting magnet facility and a newly developed, variable-angle, variable-temperature measurement capability.



Mike Abrecht transferring liquid He to an experiment dewar for the measurement of magnetoresistance.

Customer Needs

The project serves industry primarily in two areas. First is the need to develop a reliable measurement capability in the severe environment of superconductor applications: low temperature, high magnetic field, and high stress. The data are being used, for example, in the design of superconducting magnets for the magnetic-resonance-imaging (**MRI**) industry, which provides invaluable medical data for health care, and contributes 2 billion dollars per year to the U.S. economy.

The second area is to provide data and feedback to industry for the development of high-performance superconductors. This is especially exciting because of the recent deregulation of the electric power utilities and the attendant large effort being devoted to develop superconductors for power conditioning and enhanced power-transmission capability. We receive numerous requests, from both industry and government agencies, for reliable electromechanical data to help guide their efforts in research and development in this critical growth period.

The recent success of the second generation of high-temperature superconductors has brought with it new measurement problems in handling these brittle conductors. We have the expertise and equipment to address these problems. Stress and strain management is one of the key parameters needed to move the second-generation high-temperature coated conductors to the market place. The project utilizes the expertise and unique electromechanical measurement facilities at NIST to provide performance feedback and engineering data to companies and national laboratories fabricating these conductors in order to guide their decisions at this critical phase of coated-conductor development.

Technical Strategy

Our project has a long history of unique measurement service in the specialized area of electromechanical metrology. Significant emphasis is placed on an integrated approach. We provide industry with first measurements of new materials, specializing in cost-effective testing at currents less than 1000 amperes. Consultation is also provided to industry on developing its own measurements for routine testing. We also provide consultation on metrology to the magnet industry to predict and test the performance of very large cables with capacities on the order of 10 000 amperes, based on our tests at smaller scale. In short, our strategy has consistently been to sustain a small, well connected team approach with industry.

Electromechanical Measurements of Superconductors — We have developed an array of specialized measurement systems to test the effects of mechanical stresses on the electrical performance of superconducting materials. The objective is to simulate the operating conditions to which a superconductor will be subjected in magnet applications. In particular, since most technologically important superconductors are brittle, we need to know the value of strain at which fractures occur in the superconductor. This value is referred to as the irreversible strain limit, since the damage caused by the formation of cracks is permanent. The effect of cracks is *extrinsic*. In contrast, below the irreversible strain, there exists an elastic strain regime where the effect of strain is *intrinsic* to the superconductor. In this elastic regime, the variation in the critical-current density (J_c) with strain, if any, is reversible and is primarily associated with changes in the superconductor's fundamental properties, such as the critical temperature (T_c) and the upper critical field (H_{c2}), as well as changes in the superconductor's microstructure due to the application of strain.

Measurement Facilities — Extensive, advanced measurement facilities are available, including high-field (18.5 teslas) and split-pair magnets, servohydraulic mechanical testing systems, and state-of-the-art measurement probes. These probes are used for research on the effects of axial tensile strain and transverse compressive strain on critical current; measurement of cryogenic stress-strain characteristics; composite magnetic coil testing; and variable-temperature magnetoresistance measurements. Our electromechanical test capability for superconductors is one of the few of its kind in the world, and the only one providing specialized measurements for U.S. superconductor manufacturers.

Collaboration with Other Government Agencies — These measurements are an important element of our ongoing work with the U.S. Department of Energy (**DOE**). The DOE Office of High Energy Physics sponsors our research on electromechanical properties of candidate superconductors for particle-accelerator magnets. These materials include low-temperature superconductors (Nb_3Sn, Nb_3Al, and MgB_2), and high-temperature superconductors — Bi-Sr-Ca-Cu-O (**BSCCO**) and Y-Ba-Cu-O (**YBCO**) — including conductors made on rolling-assisted, biaxially textured substrates (**RABiTS**) and conductors made by ion-beam-assisted deposition (**IBAD**). The purpose of the database produced from these measurements is to allow the magnet industry to design reliable superconducting magnet systems. Our research is also sponsored by the DOE Office of Electric Transmission and Distribution. Here, we focus on high-temperature superconductors for power applications, including power-conditioning systems, motors and generators, transformers, magnetic energy storage, and transmission lines. In all these applications, the electromechanical properties of these inherently brittle materials play an important role in determining their successful utilization.

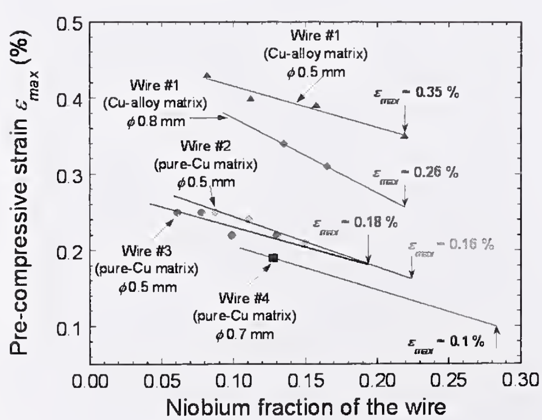
Scaling Laws for Magnet Design — In the area of low-temperature superconductors, we have embarked on a fundamental program to generalize the Strain Scaling Law (**SSL**), a magnet design relationship we discovered two decades ago. Since then, the SSL has been used in the structural design of most large magnets based on superconductors with the A-15 crystal structure. However, this relationship is a one-dimensional law, whereas magnet design is three-dimensional. Current practice is to generalize the SSL by assuming that distortional strain, rather than hydrostatic strain, dominates the effect. Recent measurements in our laboratory suggest however that this assumption is invalid. We are now developing a measurement system to carefully determine the three-dimensional strain effects in A-15 superconductors. The importance of these measurements for very large accelerator magnets is considerable. The Strain Scaling Law is now also being developed for high-temperature superconductors since we recently discovered that practical high-temperature superconductors exhibit an intrinsic axial-strain effect.

Accomplishments

- **New Measurement Method for Marginally Stable Superconductor Wires** — The next generation of particle accelerators for high-energy physics, and magnet systems for nuclear magnetic resonance (NMR) spectroscopy, will require the development of a new type of superconducting niobium-tin wire able to carry extremely high currents at high magnetic fields. One way to achieve high currents is to push the density of superconductor filaments in composite wires to new limits. Oxford Superconductor Technology (Carteret, NJ) has successfully demonstrated the feasibility of this concept. However, this could significantly reduce the beneficial "pre-compressive strain" in these conductors upon cooling, an important parameter for magnet design. Our superconductor electromechanical testing system is the only one in the U.S. that utilizes stress-free cooling, which is essential for a direct measurement of pre-compressive strain. Unfortunately, the new niobium-tin wires, owing to their relatively small amount of copper stabilizer, are only marginally stable, which makes electrical characterization extremely challenging. Hence, a new measurement technique was required that did not compromise the stress-free cooling advantage.

The technique consists of measuring critical-current density (the maximum lossless current density that a superconductor can carry) versus axial strain for a number of copper-plated specimens of the same wire with different amounts of copper. We then deduced the strain properties of the virgin (non-copper-plated) wire by an extrapolation technique. Copper plating made the niobium-tin wires electrically stable enough to characterize, but the extra copper also influenced the value of the pre-compressive strain (ε_{max}); hence the need for extrapolation. We confirmed that ε_{max} indeed decreased linearly with increasing niobium fraction. However, we found that other parameters such as the matrix material and wire diameter also influence ε_{max}.

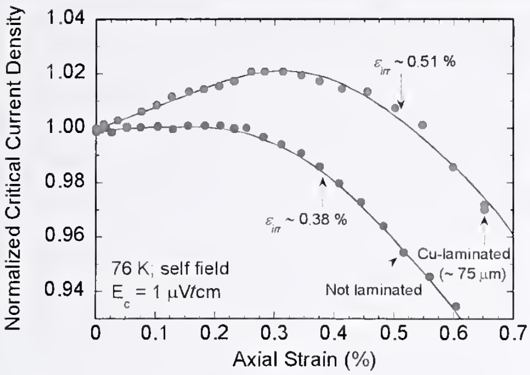
The pre-compressive strain for high-niobium-fraction wires can be reduced to about 0.1 percent, a very small strain window for magnet design. Fortunately, we also found that the use of copper alloys, instead of pure copper — along with small wire diameters — substantially mitigates the problem and provides reasonable strain operating margins in these high performance conductors. The data were used by Oxford Superconductor Technology to make immediate decisions regarding the conductor design for a new NMR system.



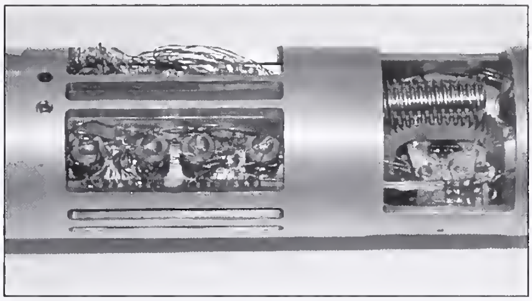
Pre-compressive strain ε_{max} versus Nb fraction for several niobium-tin wires with high niobium density. Data were obtained using a new measurement method developed by EEEL researchers for marginally stable superconductor wires.

■ **Copper Stabilizer Improves Coated Superconductors' Strain Tolerance** — High-temperature superconductor (**HTS**) wires are now being fabricated in kilometer lengths, providing the basis for a new generation of electric power devices, including high power-density motors and generators, transmission lines, and power conditioners. The development of HTS technology is expected to play a crucial role in maintaining the reliability of the power grid and upgrading power delivery to core urban areas. The most promising superconductor candidate for replacing ageing utility equipment is the highly textured Y-Ba-Cu-O (**YBCO**) compound deposited on buffered flexible metallic substrates. These "coated conductors" have a much higher current-carrying capacity compared to the Bi-Sr-Ca-Cu-O (**BSCCO**) tapes now commercially available. Whereas BSCCO tapes experience permanent damage when subjected to axial strains less than 0.2 percent, we demonstrated last year that the formation of cracks in the new YBCO system does not commence until subjected to strains higher than 0.38 percent, almost a two-fold increase in strain tolerance. This resilience of YBCO to strain is providing a strong motivation to produce commercial lengths of this "second generation" conductor, especially for the design of electric generators for which strain tolerance requirements have been raised to 0.4 percent.

This year, we found that adding a Cu layer to the YBCO coated-conductor architecture extends the irreversible strain limit (ε_{irr}) of this composite even further, from 0.38 percent to more than 0.5 percent. This markedly widens the strain window for coated-conductor applications and takes it beyond even the most demanding benchmark for large-scale superconducting generators. These measurements were undertaken in close collaboration with conductor manufacturers American Superconductor (Westborough, MA) and SuperPower (Schenectady, NY), who are incorporating the stabilizer layers either by Cu-lamination or Cu-plating. The original motivation for adding the Cu layers was to improve the electric and thermal stability of the conductor; the strain-tolerance dividend was unexpected. We can relate this remarkable result to the mismatch of thermal contraction between Cu and the other components of the composite. During sample cooling from processing temperatures to the cryogenic operating temperatures, the Cu layer exerts an additional pre-compressive strain on the YBCO film, and hence extends the irreversible strain ε_{irr} where permanent damage occurs. The Cu may also be acting as a crack arrester, which further improves the strain tolerance.



Normalized critical current density as a function of mechanical tensile strain for unlaminated and Cu-laminated YBCO coated conductor. The Cu stabilization layer extends the irreversible strain limit ε_{irr} of the composite from 0.38 percent to more than 0.5 percent.



Photograph of a new magnetoresistance probe designed to investigate carbon nanostructures. At the right end of the probe, the photo shows the stepper-motor-controlled worm-gear system and sample stage, which allow precise angle-dependent, high-field measurements.

■ **New Magnetoresistance Apparatus to Probe Carbon Nanostructures** — Electronic properties of materials change markedly as their dimensions approach those of a few atomic layers. Carbon nanostructures (including graphite sheets, single-walled carbon nanotubes, and multi-walled carbon nanotubes) are prime examples of such potentially useful materials, although some of their very fundamental properties remain controversial. Characterization of these structures at high magnetic fields is one of the principal methods for determining the existence of ballistic conduction, for example, which could be the foundation for a new generation of nanoelectronic devices.

We have designed and recently commissioned an apparatus to measure magnetoresistance of these highly directional structures in fields up to 18.5 teslas. (For comparison, the Earth's magnetic field is only about 0.05 millitesla.) The apparatus automatically acquires data as a function of magnetic-field magnitude, angle, and temperature. It was designed to also be compatible with the very-high-field magnet facilities at the National High Magnetic Field Laboratory at Florida State University, permitting the extension of EEEL's measurements to fields up to 30 teslas. Magnetic field mapping has commenced for nanotubes fabricated at NIST and Rice University as well as for graphitic sheet structures manufactured by a nanotechnology research team at Georgia Institute of Technology. Magnetic-field angle can be varied with a resolution of better than 0.1 degree over a range of 130 degrees, and sample temperature can be varied over an extended range of 4.1 to 120 kelvins, with a stability of better than 3 millikelvins at 4.2 kelvins.

■ **Textbook on Cryogenic Measurement Apparatus and Methods** — A new textbook has been written on experimental techniques for cryogenic measurements to be published by Oxford University Press. It covers the design of cryogenic measurement probes and provides cryogenic materials data for their construction. Topics include thermal techniques for designing a cryogenic apparatus, selecting materials appropriate for such apparatus, how to make high-quality electrical contacts to a superconductor, and how to make reliable critical-current measurements. The textbook is written for beginning graduate students, industry measurement engineers, and materials scientists interested in learning how to design successful low-temperature measurement systems. The appendices are written for experts in the field of cryogenic measurements and include electrical, thermal, magnetic, and mechanical properties of technical materials for cryostat construction; properties of cryogenic liquids; and temperature measurement tables and thermometer properties. These appendices aim to collect in one place many of the data essential for designing new cryogenic measurement apparatus.

Recent Publications

J. W. Ekin, *Experimental Techniques for Low Temperature Measurements,* Oxford University Press, U.K., to be published.

N. Cheggour, J. W. Ekin, and C. L. H. Thieme, "Magnetic-Field Dependence of the Reversible Axial-Strain Effect in Y-Ba-Cu-O Coated Conductors," *IEEE Trans. Appl. Supercond.,* in press.

J. W. Ekin, N. Cheggour, M. Abrecht, C. C. Clickner, M. Field, S. Hong, J. Parrell, and Y. Zhang, "Compressive Prestrain in High-Niobium-Fraction Nb_3Sn Superconductors," *IEEE Trans. Appl. Supercond.,* in press.

J. W. Ekin, "Superconductors: An Emerging Power Technology," 10th Gaseous Dielectrics Conference, March 2004, in press.

Y. Xu and J. W. Ekin, "Tunneling Characteristics and Low-Frequency Noise of High-T_c Superconductor/Noble-Metal Junctions," *Phys. Rev. B* **69**, 104515/1-9 (March 2004).

N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C.L. H. Thieme, R. Feenstra, and A. Goyal," Reversible Axial-Strain Effect and Extended Strain Limits in Y-Ba-Cu-O Coatings on Deformation-Textured Substrates," *Appl. Phys. Lett.* **83**, 4223-4225 (November 2003).

N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman, "Transverse Compressive Stress Effect in Y-Ba-Cu-O Coatings on Biaxially Textured Ni and Ni-5at.%W Substrates," *IEEE Trans. Appl. Supercond.* **13**, 3530-3533 (June 2003).

J. W. Ekin, "Superconductor Contacts," in *Handbook of Superconducting Materials,* Inst. of Physics, U.K., pp. 857-887 (January 2003).

N. Cheggour, J. W. Ekin, C. C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, and N. Rutter, "Effect of Transverse Compressive Stress on Transport Critical Current Density of Y-Ba-Cu-O Coated Ni and Ni-W RABiTS Tapes," *Ceram. Trans.* **140**, 157-170 (January 2003).

N. Cheggour, J. W. Ekin, C. C. Clickner, R. Feenstra, A. Goyal, D. F. Paranthaman, D. F. Lee, D. M. Kroeger, and D. K. Christen, "Transverse Compressive Stress, Fatigue, and Magnetic Substrate Effects on the Critical Current Density of Y-Ba-Cu-O Coated RABiTS Tapes," *Adv. Cryo. Eng. (Materials)* **48**, 461-468 (January 2002).

Standards for Superconductor Characterization

Technical Contact:
Loren Goodrich

Staff-Years (FY 2004):
1 professional
1 technician

Goals

This project develops standard measurement techniques for critical current, residual resistivity ratio, and magnetic hysteresis loss, and provides quality assurance and reference data for commercial high-temperature and low-temperature superconductors. Applications supported include magnetic-resonance imaging, research magnets, fault-current limiters, magnetic energy storage, magnets for fusion confinement, motors, generators, transformers, transmission lines, synchronous condensers, high-quality-factor resonant cavities for particle accelerators, and superconducting bearings. Project members assist in the creation and management of international standards through the International Electrotechnical Commission for superconductor characterization covering all commercial applications, including electronics. The project is currently focusing on measurements of variable-temperature critical current, residual resistivity ratio, magnetic hysteresis loss, critical current of marginally stable superconductors, and the irreversible effects of changes in magnetic field and temperature on critical current.

Loren Goodrich positioning probe with superconductor wire into the bore of a high-field superconducting magnet.

Customer Needs

We serve the U.S. superconductor industry, which consists of many small companies, in the development of new metrology and standards. We participate in projects sponsored by other government agencies that involve industry, universities, and national laboratories.

The potential impact of superconductivity on electric-power systems makes this technology especially important. We focus on (1) developing new metrology needed for evolving, large-scale superconductors, (2) participating in interlaboratory comparisons needed to verify techniques and systems used by U.S. industry, and (3) developing international standards for superconductivity needed for fair and open competition and improved communication.

Technical Strategy

International Standards — With each significant advance in superconductor technology, new procedures, interlaboratory comparisons, and standards are needed. International standards for superconductivity are created through the International Electrotechnical Commission (**IEC**), Technical Committee 90 (**TC 90**).

Critical Current Measurements — One of the most important performance parameters for large-scale superconductor applications is the critical current. Critical current is difficult to measure correctly and accurately; thus, these measurements are often subject to scrutiny and debate. The figure below is an illustration of the voltage-current characteristic and two criteria for critical current. Typical criteria are electric-field strength of 10 microvolts per meter and resistivity of 10^{-14} ohm-meters.

The next generation of Nb_3Sn and Nb_3Al wires is pushing towards higher current density, less stabilizer, larger wire diameter, and higher magnetic fields. The latest Nb-Ti conductors are also pushing these limits. The resulting higher current required for critical-current measurements turns many minor problems into significant engineering challenges. For example, heating of the specimen, from many sources, during the measurement can cause a wire to appear to be thermally unstable.

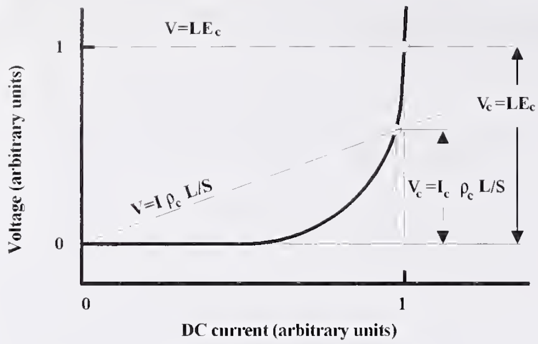


Illustration of a superconductor's voltage-current characteristic with two common criteria applied.

Magnetic Hysteresis Loss Measurements — As part of our program to characterize superconductors, we measure the magnetic hysteresis loss of marginally stable, high-current Nb_3Sn superconductors for fusion and particle-accelerator magnets. A few years ago we demonstrated that flux jumps could be suppressed during the measurement of hysteresis loss by immersing marginally stable Nb_3Sn conductors in liquid He. The increased thermal conduction affords dynamic stability against flux jumps, which allows AC losses to be estimated from the area of the magnetization-versus-field loop. Many measurements we do for superconductor wire manufacturers require special techniques to obtain accurate results.

Magnetic Thin-Film Standard Reference Material — The Magnetics Group is developing a magnetic-moment, thin-film, standard reference material for the calibration of magnetometers used in the magnetic recording industry. The properties of the films will be traceable to fundamental quantities.

Accomplishments

■ **Key Measurements for the International Thermonuclear Experimental Reactor** — Superconducting magnets are used in fusion energy projects, such as the International Thermonuclear Experimental Reactor (**ITER**), to confine and heat the plasma. The superconductors for ITER's large magnet systems are all "cable-in-conduit conductors" (**CICC**), which provide both mechanical support for the large magnetic forces and a flow path for the liquid helium required to cool the cable. The superconducting magnet must be operated below the critical current of the cable, which is a function of magnetic field and temperature. Temperature is an important variable, and the local temperature of the conductor depends on the mass-flow rate of the coolant and the distribution of the heat load along the CICC.

Earlier magnet systems that used CICC experienced unexpected degradation of their superconducting properties. To help determine the source of such degradation, we measured variable-temperature critical current of a "witness" superconductor strand that was thermally processed along with the superconducting cables used to make the latest two ITER test conductors.

The results of our unique variable-temperature measurements provide a comprehensive mapping of critical current as a function of magnetic field (0 to 12 teslas) and temperature (4 to 17 kelvins), and form a basis for evaluating CICC and magnet performance. We used the data to generate curves of electric field vs. temperature at constant current and magnetic field. These give in turn a direct indication of the temperature safety margin of the conductor.

Our results will be used by Lawrence Livermore National Laboratory, which will test CICC samples at the Plasma Physics Research Center in Villigen, Switzerland, with current up to 100 000 amperes and magnetic fields up to 12 teslas, while controlling the mass-flow rate of the coolant.

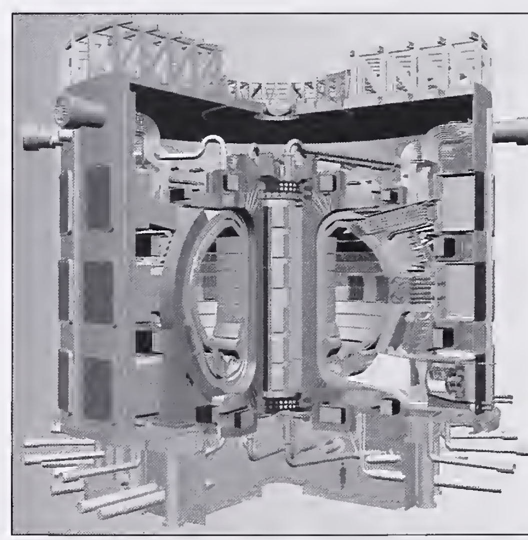
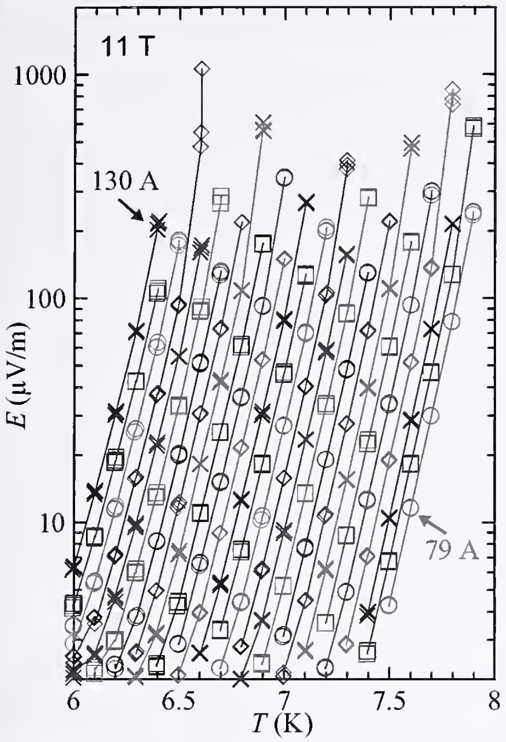


Diagram of the ITER fusion magnet systems. The central solenoid is along the vertical axis. The D-shaped structure is the toroidal field coil. At its periphery are six poloidal field coils. A human-scale figure is at the bottom. See http://www.iter.org/.



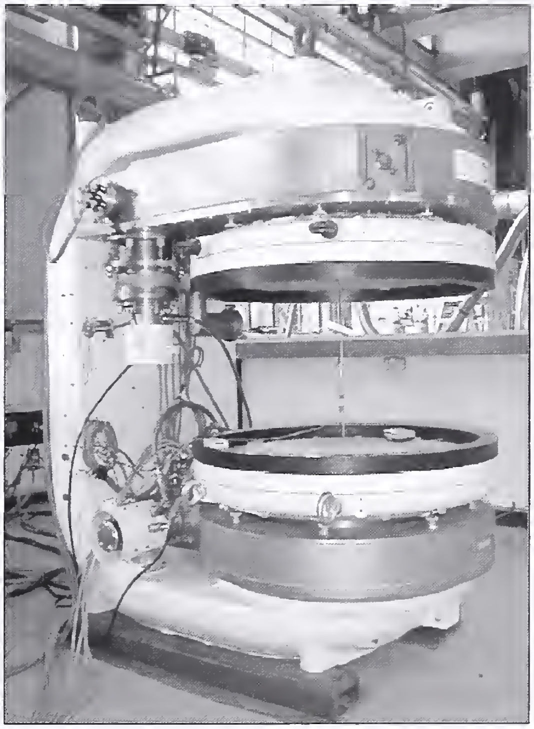
Electric field vs. temperature of the superconductor witness strand at a magnetic field of 11 teslas. These curves can be used to determine the temperature safety margin at different operating currents.

■ **Superconductor Measurements for New Type of Magnetic Resonance Imaging** — The critical current of a superconductor — the largest amount of current it can carry without reverting to the normal state — is arguably its most important parameter but the most difficult to measure accurately. This applies to new "dip-coated" bismuth-based high-temperature superconductor tapes on metal substrates.

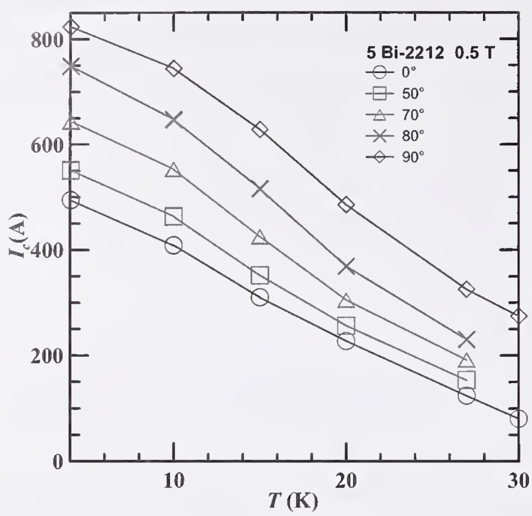
Such conductors are to be used in a Superconductivity Partnership Initiative sponsored by the Department of Energy to make the first magnetic-resonance-imaging (**MRI**) magnet to operate near 25 kelvins without the use of a liquid cryogen. The magnet will have an open geometry for greater patient comfort.

We made variable-temperature critical-current measurements on five dip-coated tape specimens for a company making conductors for this magnet. Critical current depends on temperature, magnetic field, and the angle of the magnetic field with respect to the conductor. We made measurements in magnetic fields up to 3 teslas, at various magnetic-field angles, and temperatures from 4 to 30 kelvins. Ours is the only laboratory in the U.S. that has such a multi-parameter measurement capability. The largest transport current applied to the tape samples was 900 amperes.

A multi-parameter characterization of critical current may be used to optimize MRI magnet design and conductor performance. For a given target magnetic field, the total length of conductor needed can be calculated. Magnetic-field angle can be manipulated by the addition of magnetic flux guides, which can increase the critical current by a factor of two or more. System operating cost and complexity can be reduced by operating at higher temperature.



A prototype high-temperature superconductor MRI coil and cryostat system. The coil is conductively cooled, which allows for more flexibility in the system geometry. See http://www.eere.energy. gov/superconductivity/pdfs/mri.pdf.



Critical current vs. temperature of a Bi-2212 tape at a magnetic field of 0.5 tesla and various magnetic field angles. Such curves are used to determine the safe operating current at various temperatures and field angles.

Standards Committees

- Loren Goodrich is the Chairman of IEC TC 90, the U.S. Technical Advisor to TC 90, the Convener of Working Group 2 (WG2) in TC 90, the primary U.S. Expert to WG4, WG5, WG6 and WG11, and the secondary U.S. Expert to WG1, WG3, and WG7.

- Ted Stauffer is Administrator of the U.S. Technical Advisory Group to TC 90.

Standards

In recent years, we have led in the creation and revision of several IEC standards for superconductor characterization:

- IEC 61788-1 Superconductivity – Part 1: Critical Current Measurement – DC Critical Current of Cu/Nb-Ti Composite Superconductors

- IEC 61788-2 Superconductivity – Part 2: Critical Current Measurement – DC Critical Current of Nb_3Sn Composite Superconductors

- IEC 61788-3 Superconductivity – Part 3: Critical Current Measurement – DC Critical Current of Ag-sheathed Bi-2212 and Bi-2223 Oxide Superconductor

- IEC 61788-4 Superconductivity – Part 4: Residual Resistance Ratio Measurement – Residual Resistance Ratio of Nb-Ti Composite Superconductors

- IEC 61788-5 Superconductivity – Part 5: Matrix to Superconductor Volume Ratio Measurement – Copper to Superconductor Volume Ratio of Cu/Nb-Ti Composite Superconductors

- IEC 61788-6 Superconductivity – Part 6: Mechanical Properties Measurement – Room Temperature Tensile Test of Cu/Nb-Ti Composite Superconductors

- IEC 61788-7 Superconductivity – Part 7: Electronic Characteristic Measurements – Surface Resistance of Superconductors at Microwave Frequencies

- IEC 61788-8 Superconductivity – Part 8: AC Loss Measurements – Total AC loss Measurement of Cu/Nb-Ti Composite Superconducting Wires Exposed to a Transverse Alternating Magnetic Field by a Pickup Coil Method

- IEC 61788-10 Superconductivity – Part 10: Critical Temperature Measurement – Critical Temperature of Nb-Ti, Nb_3Sn, and Bi-System Oxide Composite Superconductors by a Resistance Method

- IEC 61788-11 Superconductivity – Part 11: Residual Resistance Ratio Measurement – Residual Resistance Ratio of Nb_3Sn Composite Superconductors

- IEC 61788-12 Superconductivity – Part 12: Matrix to Superconductor Volume Ratio Measurement – Copper to Non-Copper Volume Ratio of Nb_3Sn Composite Superconducting Wires

- IEC 61788-13 Superconductivity – Part 13: AC Loss Measurements – Magnetometer Methods for Hysteresis Loss in Cu/Nb-Ti Multifilamentary Composites

- IEC 60050-815 International Electrotechnical Vocabulary – Part 815: Superconductivity

Recent Publications

L. F. Goodrich and T. C. Stauffer, "Variable-Temperature Critical-Current Measurements on a Nb_3Sn Wire," *IEEE Trans. Appl. Supercond.*, in press.

L. F. Goodrich, T. C. Stauffer, J. D. Splett, and D. Vecchia, "Observations on Unexpected Field-Angle Dependence in Magnetoresistance Measurements of High-Purity Nb," *IEEE Trans. Appl. Supercond.*, in press.

N. N. Martovetsky, P. Bruzzone, B. Stepanov, R. Wesche, C. Gung, J. V. Minervini, M. Takayasu, L. F. Goodrich, J. W. Ekin, and A. Nijhuis, "Effect of the Conduit Material on CICC Performance Under High Cycling Loads," *IEEE Trans. Appl. Supercond.*, in press.

L. F. Goodrich, T. C. Stauffer, J. D. Splett, and D. F. Vecchia, "Measuring Residual Resistivity Ratio of High-Purity Nb," *Adv. Cryo. Eng. (Materials)* **50**, 41-48 (July 2004).

L. F. Goodrich and T. C. Stauffer, "Variable-Temperature Critical-Current Measurements on a Nb-Ti Wire," *Adv. Cryo. Eng. (Materials)* **50**, 338-345 (July 2004).

C. Conery, L. F. Goodrich, and T. C. Stauffer, "More Diamagnetism Demonstrations," *Physics Teacher* **41**, 74-75 (February 2003).

B. Curé, B. Blau, D. Campi, L. F. Goodrich. I. L. Horvath, F. Kircher, R. Liikamma, J. Seppälä, R. P. Smith, J. Teuho, and L. Vieillard, "Superconducting Strand for the Compact Muon Solenoid," *IEEE Trans. Appl. Supercond.* **12**, 1014-1017 (March 2002).

L. F. Goodrich and T. C. Stauffer, "Variable Mutual Inductance in Critical-Current Measurements," *Adv. Cryo. Eng. (Materials)* **48**, 1142-1149 (May 2002).

M. Takayasu, R. G. Ballinger, R. B. Goldfarb, A. A. Squitieri, P. J. Lee, and D. C. Larbalestier, "Multifilamentary Nb_3Sn Wires Reacted in Hydrogen Gas," *Adv. Cryo. Eng. (Materials)* **48**, 986-993 (May 2002).

Appendix A: Calibration Services

The Electromagnetics Division provides a number of for-fee calibration services for radio-frequency and microwave standards. Below is a listing of those services conducted by the division, with the technical contacts. More information can be found in the NIST Calibration Services User's Guide SP250, available from the Calibration Program at NIST, 301-975-2002, calibrations@nist.gov, http://www.ts.nist.gov. The Web site provides a fee schedule.

High-Frequency Standard Capacitors and Inductors

George Free 303-497-3609

Q-Standards

George Free 303-497-3609

RF-DC Thermal Voltage and Current Converters

George Free 303-497-3609

Thermistor Detectors

Ron Ginley 303-497-3634

Scattering Parameters of Passive Multi-Port Devices

Ron Ginley 303-497-3634

Thermal Noise Measurements

Jim Randa 303-497-3150

Dimensional Verification of Coaxial Air Line Standards

George Free 303-497-3609

Dielectric and Magnetic Material Measurements

Jim Baker-Jarvis 303-497-5621

Microwave Antenna Parameter Measurements

Katie MacReynolds 303-497-3471

Field Strength Parameter Measurements

Dennis Camell 303-497-3214

Information about the availability and shipping requirements for Electromagnetics Division services may be obtained from Puanani DeLara, 303-497-5284.

Appendix B: Postdoctoral Research Associateships

NIST offers postdoctoral research associateships in collaboration with the National Research Council (NRC). Research topics and associated advisors for the Electromagnetics Division are listed below. Complete information and applications forms for all NIST NRC postdoctoral offerings are available at http://www.nas.edu/rap/ (click on "RAP SEARCH"). Contact a prospective advisor to discuss details of proposed work and the application process. If you do not find a topic that exactly matches your interest, please contact an advisor in a similar discipline. U.S. citizenship is required for NRC postdoctoral appointments.

NIST's Boulder laboratories are located adjacent to the eastern foothills of the Rocky Mountains.

Antenna Theory and Measurements I

R. C. Wittmann and M. H. Francis

A "scattering matrix description of antennas and antenna-antenna interactions" has been developed and successfully applied by researchers in this Division. Radiated fields are determined from measurements made in the near field of the antenna under test, and the theory is suitable for describing antenna interactions at arbitrary distances (not just in the far-field region). Measurement techniques (and supporting theory) must continuously be extended to keep pace with the rapid advancement in antenna design and application. Topics that need attention include (1) better accuracy-high performance systems, especially those that are satellite based, require maintenance of tighter tolerances; (2) higher frequencies-more sophisticated near-field measurement methods are needed to handle millimeter-wave applications (up to 500+ gigahertz); (3) complex phased-array antennas-large, often electronically steerable, phased arrays need special diagnostic tests to ensure optimum functionality; (4) low sidelobe antennas-military and commercial communication applications increasingly specify sidelobe levels 50 decibels or more below peak, a range where measurement by standard technique is difficult; (5) *in situ* (or remote) evaluation-many systems cannot be transported easily to a measurement laboratory; robust methods are needed for on-site testing; and (6) multiple reflections-methods are needed to mitigate errors caused by multiple reflections between the probe and test antenna. Research facilities include two planar near-field scanners, a multipurpose range for cylindrical and spherical antenna measurements, a precision extrapolation range, an anechoic chamber, a ground screen, and other EM experimental facilities, as well as excellent computational resources. We welcome proposals in these or in related areas that extend or improve the application of near-field antenna measurement methods.

Antenna Theory and Measurements II

R. C. Wittmann and M. H. Francis

In spherical near-field scanning, probe pattern information and data measured at points on a spherical surface are used to determine the fields of a test antenna anywhere beyond the measurement radius (especially in the far-field zone). Although the theory is well understood, a number of areas need further work, including (1) development of more efficient measurement and computation methods; (2) analysis of and correction for measurement errors; (3) practical pattern correction schemes for general probes; (4) development of a simplified theory for the "quasi-far-field region" where measurements are "almost" made in the far field; and (5) extensions of near-field antenna theory to other applications such as acoustics, field synthesis, and the evaluation of far-field (compact range) measurement systems. We welcome proposals on these and other topics that extend or improve the application of spherical near-field measurement techniques.

Theory for Electromagnetic Interference Problems

C. L. Holloway and D. A. Hill

Theoretical research is conducted on both forward and inverse problems in electromagnetics (EM). To characterize complex EM interference environments, a wide variety of forward problems in antennas, propagation, and scattering need to be solved. Inverse source techniques are studied to synthesize near-field antenna arrays for use in EM susceptibility testing. Inverse-scattering techniques are of interest for nondestructive evaluation of various materials. Both frequency-domain and time-domain techniques are applicable, and statistical methods are used for characterizing complex EM environments and test facilities, such as reverberation chambers. In addition to superb computational resources, excellent experimental facilities are available for verifying theoretical work. These include a time-domain range; a reverberation chamber; an anechoic chamber; TEM cells; a ground screen; planar, cylindrical, and spherical near-field scanning ranges; and an extrapolation range.

Electromagnetic Theory for Complex Environments

P. F. Wilson and D. A. Hill

Most electromagnetic field measurements seek to create a simple, well-defined environment. However, real electromagnetic environments are typically complex and poorly defined. Multiple sources and scattering objects (possibly unknown or nonstationary), complicated geometries, proximity coupling, and other real world complications make electromagnetic field measurements difficult to interpret. Statistical electromagnetic approaches are needed to quantify both real environments and complex system responses. This need already exists for large systems (*e.g.*, avionics, interconnected electronics) and the requirement will move to the component level as frequencies of operation continue to move higher (*e.g.*, high-speed computers, digital wireless systems). Research opportunities exist for developing statistical electromagnetic models. Applications include reverberation chamber test methods, coupling to complex systems, shielding of ill-defined geometries, radiation from statistically defined sources, propagation in nonstationary environments, and characterization of complex electromagnetic environments. The goal is to develop analytical descriptions for the statistics of these environments. Numerical modeling and Monte Carlo techniques will be used to verify analytical models. Excellent experimental facilities exist to generate measured data for comparison with theoretical and simulation results.

Indoor Radio Frequency Propagation Characterization for Broadband Wireless: Modeling and Measurements

C. L. Holloway

Research for accurate characterization of general indoor propagation environments is important for the design of future wireless communications systems. It is essential to understand the efficacy of broadband wireless communications systems in office complexes and other types of building environments. The indoor radio propagation channel is a very complicated environment with a variety of propagation issues that must be defined and understood. Our research objective is to develop competence in the area of indoor and indoor-to-outdoor radio propagation, and the effects on wireless communications systems. A particular goal is to develop propagation models that will address the needs of the telecommunications industry as related to the design of state-of-the-art wireless systems that can be utilized in indoor environments. This will generally be accomplished by developing theoretical models and then designing and conducting experiments for the purposes of characterizing the indoor radio frequency (RF) propagation environment. This will lead to analytical tools that can be used by wireless system designers. Advanced computational tools, as well as excellent electromagnetic measurement facilities and instrumentation are available for experimentation. Topics that need attention include coupling of energy into building structures, propagation characterization of building materials, modeling of RF propagation into and within building structures, and measurements techniques for characterizing building environments.

Theoretical Development of Equivalent Generalized Impedance Boundary Conditions

C. L. Holloway

The interaction of electromagnetic fields with rough surfaces, composite materials, thin coatings, frequency selective surfaces, and particle scattering are a few of the challenging problems of current theoretical interest. Scattering problems of this type are complicated and usually require numerical techniques. However, when the detailed surface features (roughness dimension, fiber dimensions in composites, coating thickness, scattering shapes in FSS, and particle spacing) are small compared to a wavelength, equivalent generalized impedance boundary conditions (EGIBC) can be used. These EGIBC and Maxwell's equation are all that is needed to solve these types of scattering problems. EGIBC are also very efficient in analyzing reflection problems. For example, in large electromagnetic computational codes, the use of EGIBC can eliminate the need to spatially resolve the fine detail of a particular scattering feature, which results in the abilities to solve much larger numerical problems. The proposed research direction is to use various asymptotic techniques to derive EGIBC for various electromagnetic field interactions. Specific boundary conditions will be derived so that the coefficients in the EGIBC can be interpreted in terms of electric and magnetic polarizability densities.

Fundamental Modeling for Electromagnetic Compatibility

C. L. Holloway and D. A. Hill

Analytic and numerical theoretical investigations are needed on a broad range of topics related to electromagnetic compatibility (EMC) and electromagnetic interference (EMI). The particular numerical models of interest are finite-difference time-domain, finite-elements, integral equations, and hybrid techniques. Suggested topics include printed circuit board radiation, signal integrity and coupling of high-speed digital lines and devices, lossy transmission lines, characterization and optimal design of large test facilities (*e.g.*, reverberation, anechoic, and semi-anechoic chambers), properties of electromagnetic absorbing materials, design of advanced composite and frequency selective materials, shielding effectiveness of various materials, and other coupling problems. The broad objective is to develop accurate analytic and numerical models that will advance the fundamental understanding of critical EMC/EMI issues. Extensive measurement facilities are also available with which to assess the validity of the resulting models.

Electromagnetic Theory for Time-Domain Analysis

R. T. Johnk

The transient behavior of both canonical and complex objects subjected to an electromagnetic (EM) impulse from a radiating source is studied. Although transient problems can be analyzed by inverse Fourier-transformation of frequency-domain data, the time-domain technique has several advantages over the frequency-domain technique. The broadband nature of time-domain analysis facilitates the understanding of nonlinearities, and the ability to model propagation delays provides improved physical insights related to the spatial geometry of the problem. Problems of both radiation and scattering from complex structures with both linear and nonlinear loadings are appropriate topics for study. The theoretical and experimental results will be applied to canonical problems to provide useful physical insights into the interaction of EM waves with devices and materials.

Electro-optical Technology for Electromagnetic Field Measurements

K. D. Masterson

This research focuses on developing electromagnetic (EM) field probes based on electro-optical technology and optical fiber links. Such systems provide amplitude and phase information for high-frequency EM fields throughout the radio spectrum, cause minimum distortion of the field, and are immune from EM pickup and interference in the antenna leads. They increase the accuracy and information available for characterizing EM fields. Research opportunities exist in the areas of electro-optic modulators, modulated lasers, optical fiber links (including polarization effects and controllers), and related theoretical and experimental physics. Facilities include an electro-optic probe development laboratory and extensive EM-field test facilities for experimental characterization of probes, as well as opportunities for collaborative resources in electro-optics and computational and applied mathematics.

Performance Characterization of Wireless Systems

R. B. Marks

This topic concerns the development and application of an experimental facility for characterizing the performance of wireless systems and the dependence of such performance on components, subsystems, modulation, propagation, interference, and other factors. We are primarily interested in the characterization of fixed broadband wireless access systems from 2 to 40 gigahertz. Strong opportunities exist in correlating radio frequency component characterizations to system performance. Other innovative research is also possible, particularly in testbed design and system simulation. A broad range of related measurement facilities, expertise, and other resources will be available to the researcher and close correlation with industry and with standards-developing bodies is encouraged.

RF Characterization of Nonlinear Devices

D. C. DeGroot

Nonlinearity is an important design issue and the development of a general measurement-based theory for characterizing nonlinearities is a critical need, particularly with regard to wireless telecommunications systems. Nonlinear properties of devices are difficult to accurately model, but are also challenging to measure. Our current goal is to quantitatively characterize weakly nonlinear two-port networks (typically power amplifiers) in order to predict circuit parameters (*e.g.*, power, gain, efficiency, intermodulation, distortion) under a variety of terminal conditions. Instrumentation for nonlinear characterization, nonlinear network theory, and calibration are essential elements of this measurement task. Excellent resources will be available to the researcher including the first non-proprietary nonlinear network analyzer, highly accurate (linear) on-wafer and conventional measurement capabilities, microcircuit fabrication facilities, state-of-the art computational resources, and on-site expertise in a diverse range of related disciplines.

Quantum-Based Microwave Amplitude Measurements

T. P. Crowley

We are performing proof-of-concept experiments to measure microwave signal strength based on quantum-mechanical principles. The experiments use a set of laser-cooled cesium atoms in a fountain apparatus designed for atomic clock experiments. Rabi oscillations between two hyperfine levels of the cesium ground state are measured and used to determine the RF magnetic field strength in a resonant cavity. Initial experiments have demonstrated changes with microwave power level and duration scale, as expected. The next steps in our research involve obtaining absolute measurements of the field strength, and then improving the accuracy of the measurement by constructing an apparatus optimized for microwave signal strength measurements. Ultimately, we hope to develop a technique that is applicable over a broad frequency range and can be used to characterize transfer standards. The research is a fundamental change in the approach to measuring microwave signal levels. Traditional techniques rely on the heating induced when microwave power is absorbed and are based on comparisons with DC power measurements. Uncertainties are introduced because RF and DC power are not typically dissipated in the same location. We hope that a quantum-based measurement will greatly improve the accuracy of our primary standards and lead to new applications and techniques. Available resources include a laser system for cooling cesium atoms; a cesium mini-fountain; and a wide range of microwave components, sources, and existing standards.

Microwave Power Measurements with Thin-Film Bolometers

T. P. Crowley

This project will develop new transfer standards for microwave power measurements. The most important component will be the development of a thin-film bolometer on a semiconductor substrate. This bolometer will need to be thermally isolated from the bulk of the substrate through micro-machining or other techniques. A bolometer is a resistor that is temperature dependent and therefore sensitive to incident power. The immediate need is to improve and replace thin-film bolometer mounts used in transfer standards with 2.4 millimeter connectors. These detectors are used as power standards from 50 megahertz to 50 gigahertz. However, we ultimately expect to use these transfer standards in coaxial connectors with higher frequency capability and in waveguide mounts. In addition, the sensors are the first step in the development of on-wafer power measurement capability. Development of these new bolometers is a critical requirement because commercial vendors are developing fewer products suitable as transfer standards. A wide range of microwave components, sources, and existing standards are available as well as NIST's in-house capabilities for making integrated circuits for research.

Thermal Noise Measurements

J. Randa

Theory, standards, methods, and systems are developed for highly accurate measurements of thermal electromagnetic noise from radio frequencies to millimeter waves. Current research comprises two major thrusts: developing improved methods for characterizing the noise properties of low-noise amplifiers and transistors, and developing improved calibration methods for remote-sensing radiometers. Research opportunities are supported by extensive theoretical and experimental expertise, as well as world-class noise-temperature measurement capabilities.

Electromagnetic Properties of Materials

J. R. Baker-Jarvis

Research opportunities exist for theoretical and experimental investigations related to the precise characterization of the electromagnetic properties of bulk and thin-film materials in the frequency range of 100 megahertz to 100 gigahertz. Suggested research areas include the measurement of ultra-low-loss dielectric and magnetic materials, thin films, ferroelectric materials, metamaterials and nanotechnology, the uncertainty analysis of measurement techniques, the relationship of complex permittivity to material mechanical stress, linear and nonlinear response theory, maximum entropy methods for data reduction and optimization, dielectric measurements of liquids, characterization of high-temperature superconductor films, and biased ferrite and ferroelectric measurements. In addition to excellent computational resources, a wide range of experimental resonators, well-characterized materials, laboratory instrumentation, environmental facilities (*e.g.*, a cryostat, a high-temperature chamber, and a magnetic bias capability), and a diversity of related intellectual resources are available to facilitate research.

Precision High-Speed Waveform Measurement DF Williams

P. D. Hale

We have developed an electro-optic sampling system that measures very fast electrical waveforms. This project will extend our current electrical models for the measurement system to 200 gigahertz and allow the precision measurement of waveforms with 5 picosecond rise times.

We have constructed an electro-optic sampling system with a measurement bandwidth near a terahertz. The system is designed to accurately measure electrical pulses on transmission lines printed on special NIST-constructed electro-optic substrates, and now provides NIST's most fundamental measurements of high-speed electrical pulses. This system is now being used to calibrate the output of high-speed photo diodes and oscilloscopes to 110 gigahertz. Distortion in the probes we use to inject electrical signals onto the electro-optic substrate currently limits our measurement bandwidth to 110 gigahertz. This project will focus on using data from the electro-optic sampling system itself to characterize these probes to 200 gigahertz and beyond. The result of the effort will be models for the probes that will allow us to break our current 110 gigahertz measurement barrier and characterize the fastest photodiodes, pulse sources, and oscilloscopes in the world.

On-Wafer Microwave Measurements and Standards

D. F. Williams and P. Kabos

Research opportunities exist for theoretical and experimental studies of wafer-level microwave measurement techniques in the frequency range of 50 megahertz to 110 gigahertz. Work focuses on the on-wafer measurement of *s*-parameters and signal characterization, including the development of new measurement methodologies, and modeling and analysis of single and coupled planar transmission lines. Unique opportunities exist to compare both the theoretical and experimental results.

Characterization of High-Speed Digital Interconnects and Signals

D. F. Williams, P. Kabos, P. D. Hale, and T. S. Clement

This project provides unique opportunities for theoretical and experimental studies of high-speed digital interconnects and signals. Current research focuses on adapting microwave measurement methods to noncontacting characterization of high-speed signals and the characterization of conventional, differential, and coupled differential transmission lines fabricated on silicon substrates. This research has strong relevance to industry and collaborators will have access to measurement equipment at frequencies beyond 110 gigahertz.

Ultrafast Signal Measurement for High-Speed Integrated Circuits

D. F. Williams, P. Kabos, P. D. Hale, and T. S. Clement

We study methods for measuring and calibrating ultrafast signals with 110 gigahertz to 400 gigahertz bandwidths on high-speed integrated circuits. Methods that we are currently investigating include the use of electro-optic interactions with bandwidths of many terahertz. Research focuses on fully calibratable measurement of signals in printed transmission lines with low uncertainty, extension of measurements to 110 gigahertz in the near future, and extension to 400 gigahertz in the next five years.

High-Resolution Noninvasive High-Speed Nanoscale Probing and Field Imaging

P. Kabos and J. R. Baker-Jarvis

Few experimental tools are currently available that can probe high-speed/frequency properties of materials and devices on a molecular scale. Proposals are invited for high-frequency accurate noninvasive nanoscale probing and theory; electromagnetic field imaging; and measurements of voltage, current, and materials properties. The objective is to develop the fundamental metrology; the instruments and standards that will make it possible to perform high-speed voltage and current measurements necessary for the characterization of high-speed, high-performance ultrahigh-density nano- and molecular-electronics devices; and of the electromagnetic properties of nano-engineered, artificial, and carbon-nanotube-based materials and devices. Film deposition, lithography and state-of-the-art microwave test systems, probe stations, and atomic force microscopy facilities are available for the proposed research.

Superconductor Measurements

L.F. Goodrich

We develop and evaluate measurement techniques to determine the critical parameters and matrix properties of superconductors. Capabilities include variable-temperature critical-current measurement, low-noise current supplies up to 3000 amperes, high-field magnets up to 18 teslas, and voltage sensitivity to 1 nanovolt. We study conventional superconductors (NbTi and Nb_3Sn) and the newer high-transition-temperature materials. We conduct fundamental studies of the superconducting-normal transitions and the parameters that affect their accurate determination, such as current transfer, strain, or inhomogeneities in materials and fields. We develop theoretical models to interpret current redistribution and component interactions in composite superconductors.

High-Field Superconductor Research

J. W. Ekin

This research program is interdisciplinary, encompassing the physical, mechanical, and electrical properties of high-field superconducting materials and composites. Experimental programs include the effect of stress and fatigue on superconducting critical parameters, electrical and/or metallurgical properties. Very high-field magnet systems, power supplies, servohydraulic mechanical test systems, and analytic microscopy facilities are available. Research is conducted on new types of high current density superconductors and superconductor stabilization that are being developed for very high-field magnet and accelerator applications. Theoretical studies concentrate on flux pinning and the intrinsic effect of strain on the superconducting state.

High-Power, High T_c Superconductors

J. W. Ekin

A unique feature of this program is that we use our expertise in electromechanical measurements and contact interface studies to work more closely with research laboratories in industry and at major universities to develop new types of high-T_c superconductors for emerging power technologies in transmission lines and high-power-density rotating machinery. We are interested in all aspects of high-T_c superconductor research including the mechanical, magnetic field, and electrical limits of the new class of thick-film YBCO coated conductors. Our film deposition and cleanroom facilities are fully equipped for fabrication and micropatterning of film conductors, contacts, and research test structures. Particular effort now focuses on understanding the basic properties of YBCO film superconductors, new reinforced low porosity Bi-2223 and Bi-2212 superconductors, and MgB_2 multifilamentary composite conductors.

Magnetism in Thin Films and Surfaces

D. P. Pappas

Opportunities are available to work in a wide range of topics. Areas of interest include spin polarized electron attenuation in solids, surface magnetic studies, magnetoresistive microscopy, high-sensitivity magnetoresistive sensors, and perpendicular magnetic recording materials.

Quantum Computing Materials Development

D. P. Pappas

We have recently identified decoherence mechanisms in the tunnel junction in quantum bit (qubit) devices. Our devices are based on phase sensitive qubits and include a Josephson junction that is biased to provide a nonlinear potential. We have observed conductance fluctuations that give rise to resonances near the quantum phase transition. In order to reduce these resonances, we are developing new materials for the tunnel barriers. Possible materials include epitaxial aluminum oxide, amorphous aluminum nitride, and boron nitride. The successful candidate for this position will grow barriers in a UHV sputter chamber. The chamber is part of a cluster that has UHV surface characterization tools including low temperature STM, Auger, and LEED. The opportunity also includes fabrication of qubits in the cleanroom and testing.

Molecular and Nano-Magnetism

S. Russek

Ultra-small magnetic structures will be fabricated using both conventional nanolithography techniques (e-beam and scanned probe lithographies) and chemical synthetic techniques. The systems studied may include molecular nanomagnets (*e.g.*, Mn-12), carbon nanotubes grown on magnetic nanoparticles, patterned longitudinal and perpendicular media, and nanodevices. The goal of this research will be to understand the physics of ultras mall magnetic structures, their implications for the limits of magnetic data storage, and to develop novel nanoscale devices. The magnetization and switching processes will be studied as a function of size, shape, and temperature to characterize thermally activated and quantum mechanical tunneling transitions. The high-frequency properties (1 gigahertz to 150 gigahertz) will be studied using high-frequency electron spin resonance, ferromagnetic resonance, and transport properties. The molecular nanomagnets and magnetic nanostructures will be incorporated into thin-film device structures to explore potential device applications.

Spintronic Devices and Materials

S. Russek

Spin-dependent transport is a widely used, yet poorly understood phenomenon. Giant magnetoresistive (GMR) devices and magnetic tunnel junctions (MTJ) are being developed for use in magnetic recording heads, magnetoresistive random access memories (MRAM), and industrial magnetic sensors. The market for these devices is enormous, in the tens of billions of dollars. New types of spintronics devices such as spin-transfer oscillators and spin-dependent semiconductor devices may open up a wide range of new applications. The goal of this research is to develop a better fundamental understanding of spin-dependent transport in magnetic metals, normal metals, conducting oxides, and semiconductors. This research involves the fabrication of novel spintronic devices such as GMR, MTJ, and spin transfer devices using a state-of-the-art, eight-source, ultrahigh vacuum eight-source deposition system and a combination of optical, e-beam, and scanned probe lithography. Electrical measurements, over a wide range of temperature, field, and frequency, will be used to characterize spin dependent transport properties with a particular emphasis on high-frequency and noise properties of the devices.

High-Frequency Characterization of Novel Thin-Film Materials

S. Russek, J. R. Baker-Jarvis, and P. Kabos

The goal of this project is to fabricate novel nano-engineered thin-film materials and measure their electromagnetic properties in the 1-100 gigahertz regime. The materials include nanostructured materials, composite ferromagnetic-ferroelectric materials, "left-handed" materials, and frequency-tunable materials. The materials can be fabricated using an ultra-high vacuum, eight-source sputtering system; a laser ablation system; and optical and e-beam lithography systems. The dielectric and magnetic properties can be engineered by patterning arrays of elements on two different length scales. Patterning on a scale comparable to the excitation wavelength — about 1 millimeter — will allow the development of artificial crystals (photonic band gap materials) in the microwave regime. Patterning on a scale much shorter than the wavelength, 10-100 nanometers, will allow the permittivity, permeability, and conductivity to be engineered and controlled to have new functionalities. Examples of such materials engineering include light- and field-tunable exchange coupling, low-loss amorphous/nanoparticle composites, negative-epsilon negative-mu ("left handed") systems, and ferroelectric-ferromagnetic multilayers. Measurements will be conducted on state-of-the-art, 100 gigahertz microwave test systems and cryogenic microwave probe stations.

High-Speed Magnetic Phenomena

T. J. Silva

Experimental methods to determine fundamental limits to the data transfer rate of magnetic devices are being developed. Both low-coercivity ("soft") and high-coercivity ("hard") magnetic materials are studied. Experimental techniques include electrically sampled inductive detection and time-resolved magneto-optics for the study of soft magnetic materials. Quantitative Kerr microscopy is used for the measurement of switching speed in hard magnetic materials. Extensive facilities include a 20-gigahertz sampling oscilloscope, a 50 femtosecond mode-locked Ti:sapphire laser, and a digital Kerr microscope with a high-performance chilled charge-coupled device camera. Commercial and experimental solid-state instrumentation is used for the generation of microwave pulses. Waveguide technology is employed to deliver subnanosecond magnetic field pulses to samples. Waveguide structures are lithographically fabricated on site in a state-of-the-art cleanroom, which includes mask generation facilities. Applicants are encouraged who have a strong experimental background in magnetism, especially high-frequency magnetic phenomena such as ferromagnetic resonance.

Nonlinear Magneto-optics

T. J. Silva

The second-harmonic magneto-optic Kerr effect (SH-MOKE) is under investigation as a tool for the study of interfacial magnetism. SH-MOKE shows strong sensitivity to the magnetization at optically accessible interfaces between ferromagnetic and non-ferromagnetic films, yet SH-MOKE does not require exotic facilities, such as ultrahigh vacuum (UHV) or synchrotron radiation.. Therefore, SH-MOKE shows great promise as an industrial diagnostic instrument for the optimization of giant magnetoresistive sensors and magnetic tunnel junctions, where interfacial magnetism strongly influences device performance. SH-MOKE also exhibits a strong magneto-optic signal, with the magnetic contrast approaching 60 percent in some sample systems. Extensive resources for the study of SH-MOKE include a mode-locked 50 femtosecond Ti:sapphire laser, coincident photon detection electronics, photo-elastic modulators, lock-in amplifiers, and sample translation stages. Samples may be produced on site with a state-of-the-art, eight-source UHV sputtering system. Applicants are preferred with a strong experimental background in magnetic thin films, magnetic multilayers, magneto-optics, and/or nonlinear optics.

Thermal Instability of Magnetic Thin Films

T. J. Silva

As the grain size of thin-film magnetic recording media steadily decreases with increasing areal capacities, we are concerned that recorded information may be erased as a result of thermally activated switching of the individual grains-the so-called "superparamagnetic limit." Our goal is to understand the fundamental mechanisms that result in thermal erasure through the measurement of various phenomena, including magnetic viscosity and the time dependence of coercivity. Emphasis is placed on determining the thermal stability of media over a wide range of time scales, from those accessible with large-scale magnetometers to those that use pulsed microwave fields. The final goal is a measurement technique for the determination of data stability in media without resorting to mean-time-before-failure analysis. Extensive facilities include numerous magnetometers (vibrating-sample magnetometer, alternating gradient magnetometer, SQUID magnetometer), a transmission electron microscope for the determination of grain size, and a state-of-the-art, eight-source ultrahigh vacuum sputtering system for the preparation of samples. Applicants with a strong experimental background in magnetism-especially magnetic thin-film preparation and characterization-are encouraged to apply.

Spintronics

T. J. Silva

This project focuses on the investigation of spin dynamics in semiconductors. Time-resolved magneto-optics is used to generate and study coherent spin dynamics in direct bandgap semiconductors. Equipment includes a femtosecond Ti:sapphire laser system, an optical cryostat to vary temperature from 4 to 300 kelvins with a superconducting magnet capable of 8 tesla magnetic fields, and comprehensive optical polarization analysis facilities. Investigations will determine the feasibility of coherent spin diffusion from ferromagnetic contacts. Mechanisms to be studied include near-field coupling of the electromagnetic fields from the preceding spins in a nanomagnet and direct diffusion across a forward-biased Schottky junction.

Magnetic Measurement of Hydrogen in Batteries and Fuel Cells

R. B. Goldfarb

Low-mass Zr and Mg "AB_2" alloys are candidates to replace lanthanide rare-earth alloys used in Ni-metal-hydride, solid-state, electrolyte battery cathodes in order to achieve higher gravimetric energy densities, greater number of recharge cycles, better durability and corrosion resistance, and lower cost. The utility of these alloys will depend on their hydrogen-storage capacity and rates of absorption and desorption at ambient temperature. Such materials would also have application for hydrogen storage in fuel cells. Hydrogen in Ni-metal hydrides may be either bound or diffusible (*i.e.*, useful in absorption/desorption). Nondestructive magnetic measurement techniques could provide a convenient tool to screen candidate alloys for their capacity to store and release diffusible hydrogen. In addition to "AB_2" alloys, measurements are made on "AB_5" alloys such as La-Ni-Co and La-Ni-Al. Work is done in close collaboration with the Colorado School of Mines in Golden, Colorado. Applicants should have a strong background in chemistry or materials science.

In Vivo Electron Paramagnetic Resonance

R. B. Goldfarb and P. Kabos

We welcome proposals for the development of new measurement techniques based on electron paramagnetic resonance to be used for *in vivo* medical diagnostics. Techniques developed at NIST would involve artificial phantoms, not biological materials. Experiments on animal models would be performed at collaborating institutions.

Linear and Nonlinear Damping and Relaxation in Magnetic Information Storage Materials

R. B. Goldfarb, P. Kabos, and S. Russek

As magnetic recording moves well into the gigahertz frequency regime, the mechanisms that limit the precession dynamics and decay time of the spin system in magnetic thin films become limiting factors in recording head design, materials selection, and magnetoelectronics applications. Low- and high-power ferromagnetic resonance (FMR), microstripline FMR, off-resonance effective linewidth techniques, and Brillouin light scattering provide critical tools needed to elucidate these processes and develop optimum thin-film materials for these applications. In this program, metallic thin materials, metal-oxide multilayers, and nano-oxide films will be fabricated and used for research on the fundamental loss processes that limit magnetic switching and large-angle precession dynamics response times. Effectively all of the established tools of high-frequency magnetics research will be used on this topic. The use of FMR techniques over a wide range of frequencies from 1 to 100 gigahertz and different static and pumping field geometries will help separate intrinsic loss processes (*e.g.*, magnon-electron scattering) from extrinsic processes (*e.g.*, two-magnon relaxation). Effective linewidth and spin-wave instability measurements will be used to probe the wave vector dependences of the intrinsic processes. High-power above-threshold spin-wave instability, Brillouin light scattering, and FMR force microscopy techniques will give new information on the actual nonlinear response of these film materials systems. This program will utilize facilities and capabilities developed at both NIST and in the laboratory of Professor Carl Patton at Colorado State University.

New Magnetoresistive Sensors for Medical and Other Applications

D. P. Pappas

We invite proposals for the development and electronic implementation of low-noise, high-sensitivity, ambient-temperature, magnetoresistive field sensors for applications in security, medicine, and magnetic disk drive read heads. Medical applications include magnetocardiography, magneto-encephalography, and in-vivo measurement of iron stores in the body. We have facilities for microelectronic device fabrication and testing.

Chip-Scale Magnetic Resonance Imaging Microscope

J. M. Moreland

Conventional magnetic resonance imaging (MRI) systems are limited in resolution because of the noise of inductive detector which limits sensitivity as well as difficulties generating field gradients sufficient for narrow sample slice discrimination. By using micromechanical cantilever oscillators as magnetic sensors and by reducing the dimensions of the gradient coils significant improvements in sensitivity and resolution can be made. In particular, we have recently demonstrated several micromechanical magnetometers including a magnetic resonance force microscope, a torque magnetometer, and a micromechanical calorimeter. These magnetometers operate on the principle of modulating the magnetic resonance excitation of a sample attached to a microcantilever at the cantilevers resonance frequency. Our goal is to optimize these novel detectors for biological applications including *in vivo* imaging of cell organelles and membranes. The main challenge is to develop integrated microsystems with micro fabricated DC and RF field sources, magnetic sensors, and field gradient coils. Ideally, the chip should be adaptable to microt1uidic environments.

Nanoscale Imaging for Magnetic Technology

J. M. Moreland

The magnetic storage industry has advanced to the stage where nanometer-scale morphological and physical properties play an important role in current and future disk drive performance. In its many forms, scanned probe microscopy (SPM) can be used to measure roughness, device dimensions, electromagnetic field patterns, and various physical processes at nanometer scales, which provides important information about the fundamental operation and limitations of drive components. Our goal is to help tailor SPM techniques for these applications. We are investigating scanning tunneling microscopy, atomic force microscopy, magnetic force microscopy, scanning potentiometry, and scanning thermometry for their usefulness.

Atomic Scale Information Storage

J. M. Moreland

We are investigating novel techniques capable of ultrahigh density information storage at atomic scales. Devices that rely on magnetic, electrostatic, morphological, or other variations in storage media approaching atomic scales are considered in response to a recognized need to shift information storage paradigms in the 21st century. Scanned probe microscopy is being used to write atomic scale "bits" and to study the properties and fundamental recording processes in different kinds of storage media.

Micro-Electromechanical Systems for Metrology

J. M. Moreland

We are developing micro-electromechanical systems (MEMS) with integrated components for precision measurement purposes. Work focuses on the following goals: (1) improving the performance of fundamental standards instrumentation by developing novel detectors and more fully integrated measurement systems, (2) exploring the impact of MEMS and MEMS-based metrology on the future development of the microelectronics and data storage industries, and (3) improving the manufacturing yield with MEMS probe assemblies designed for production line testing. Our cleanroom facility is fully equipped for bulk and surface micromachining of silicon wafers including design, fabrication, and testing tools. We are interested in all aspects of research including the development of novel MEMS structures, as well as the testing and integration of MEMS structures into precision measurement instruments.

Single-Molecule Manipulation and Measurement

J. M. Moreland

We are developing a nanoelectromechanical system platform change for single biomolecule manipulation and measurement. Measurements to determine the structure and function of protein and DNA are currently made using large populations of molecules rather than single molecules. Researchers in biotechnology have shown that the behavior of single molecules in living systems can be different from results obtained by measuring the statistical average of large populations of molecules. The limitation in making single molecule measurements is primarily due to the lack of measurement tools and methods that are capable of isolating, manipulating, and probing the behavior and structure of the molecules. As a result, there is a rapidly growing interest in the development and application of nanotechnology to support single-molecule measurements.

Linear and Nonlinear Microwave Response of Oxide Thin Films and Devices

J. C. Booth

Thin-film oxide materials and devices possess extraordinary properties that could revolutionize many different areas of modern electronics. For example, the low microwave surface resistance R_s of the high-T_c superconductors makes them ideal for a wide variety of high-performance devices and circuits. However, fundamental questions still remain with regard to the origins of losses in these materials at microwave frequencies, as well as to the origin of the nonlinear response that is observed under large signal conditions. We address these fundamental questions with measurements of the linear properties (surface resistance) as well as the nonlinear response (third-order intercept and intermodulation) of unpatterned thin films and also patterned devices at low to moderate power levels. Other measurements (such as inductive critical-current measurements and high-power microwave transmission measurements) address the response of these materials under high-power conditions. In all of the above measurements, special attention is paid to the relationship between the electronic properties of interest and film growth and device fabrication processes. Our goals are to understand the physical origins of both the losses and nonlinearity in these systems while simultaneously developing processes to optimize performance of microwave device incorporating these materials.

Appendix C: Prefixes for the International System of Units (SI)

Multiplication Factor	Prefix	Symbol	Multiplication Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Appendix D:
Units for Magnetic Properties

Symbol	Quantity	Conversion from Gaussian and cgs emu to SI
Φ	magnetic flux	1 Mx $\rightarrow 10^{-8}$ Wb $= 10^{-8}$ V·s
B	magnetic flux density, magnetic induction	1 G $\rightarrow 10^{-4}$ T $= 10^{-4}$ Wb/m^2
H	magnetic field strength	1 Oe $\rightarrow 10^3/(4\pi)$ A/m
m	magnetic moment	1 erg/G = 1 emu $\rightarrow 10^{-3}$ A·m^2 $= 10^{-3}$ J/T
M	magnetization	1 erg/(G·cm^3) = 1 emu/cm^3 $\rightarrow 10^3$ A/m
$4\pi M$	magnetization	1 G $\rightarrow 10^3/(4\pi)$ A/m
σ	mass magnetization, specific magnetization	1 erg/(G·g) = 1 emu/g $\rightarrow$ 1 A·m^2/kg
j	magnetic dipole moment	1 erg/G = 1 emu $\rightarrow 4\pi \times 10^{-10}$ Wb·m
J	magnetic polarization	1 erg/(G·cm^3) = 1 emu/cm^3 $\rightarrow 4\pi \times 10^{-4}$ T
χ, κ	susceptibility	$1 \rightarrow 4\pi$
χ_ρ	mass susceptibility	1 cm^3/g $\rightarrow 4\pi \times 10^{-3}$ m^3/kg
μ	permeability	$1 \rightarrow 4\pi \times 10^{-7}$ H/m $= 4\pi \times 10^{-7}$ Wb/(A·m)
μ_r	relative permeability	$\mu \rightarrow \mu_r$
w, W	energy density	1 erg/cm^3 $\rightarrow 10^{-1}$ J/m^3
N, D	demagnetizing factor	$1 \rightarrow 1/(4\pi)$

Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted, Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

Appendix E: Symbols for the Chemical Elements

Symbol	Element	Symbol	Element	Symbol	Element
Ac	Actinium	Gd	Gadolinium	Po	Polonium
Ag	Silver	Ge	Germanium	Pr	Praseodymium
Al	Aluminum	H	Hydrogen	Pt	Platinum
Am	Americium	He	Helium	Pu	Plutonium
Ar	Argon	Hf	Hafnium	Ra	Radium
As	Arsenic	Hg	Mercury	Rb	Rubidium
At	Astatine	Ho	Holmium	Re	Rhenium
Au	Gold	I	Iodine	Rh	Rhodium
B	Boron	In	Indium	Rn	Radon
Ba	Barium	Ir	Iridium	Ru	Ruthenium
Be	Beryllium	K	Potassium	S	Sulfur
Bi	Bismuth	Kr	Krypton	Sb	Antimony
Bk	Berkelium	La	Lanthanum	Sc	Scandium
Br	Bromine	Li	Lithium	Se	Selenium
C	Carbon	Lr	Lawrencium	Si	Silicon
Ca	Calcium	Lu	Lutetium	Sm	Samarium
Cd	Cadmium	Md	Mendelevium	Sn	Tin
Ce	Cerium	Mg	Magnesium	Sr	Strontium
Cf	Californium	Mn	Manganese	Ta	Tantalum
Cl	Chlorine	Mo	Molybdenum	Tb	Terbium
Cm	Curium	N	Nitrogen	Tc	Technetium
Co	Cobalt	Na	Sodium	Te	Tellurium
Cr	Chromium	Nb	Niobium	Th	Thorium
Cs	Cesium	Nd	Neodymium	Ti	Titanium
Cu	Copper	Ne	Neon	Tl	Thallium
Dy	Dysprosium	Ni	Nickel	Tm	Thulium
Er	Erbium	No	Nobelium	U	Uranium
Es	Einsteinium	Np	Neptunium	V	Vanadium
Eu	Europium	O	Oxygen	W	Tungsten
F	Fluorine	Os	Osmium	Xe	Xenon
Fe	Iron	P	Phosphorus	Y	Yttrium
Fm	Fermium	Pa	Protactinium	Yb	Ytterbium
Fr	Francium	Pb	Lead	Zn	Zinc
Ga	Gallium	Pd	Palladium	Zr	Zirconium
		Pm	Promethium		

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