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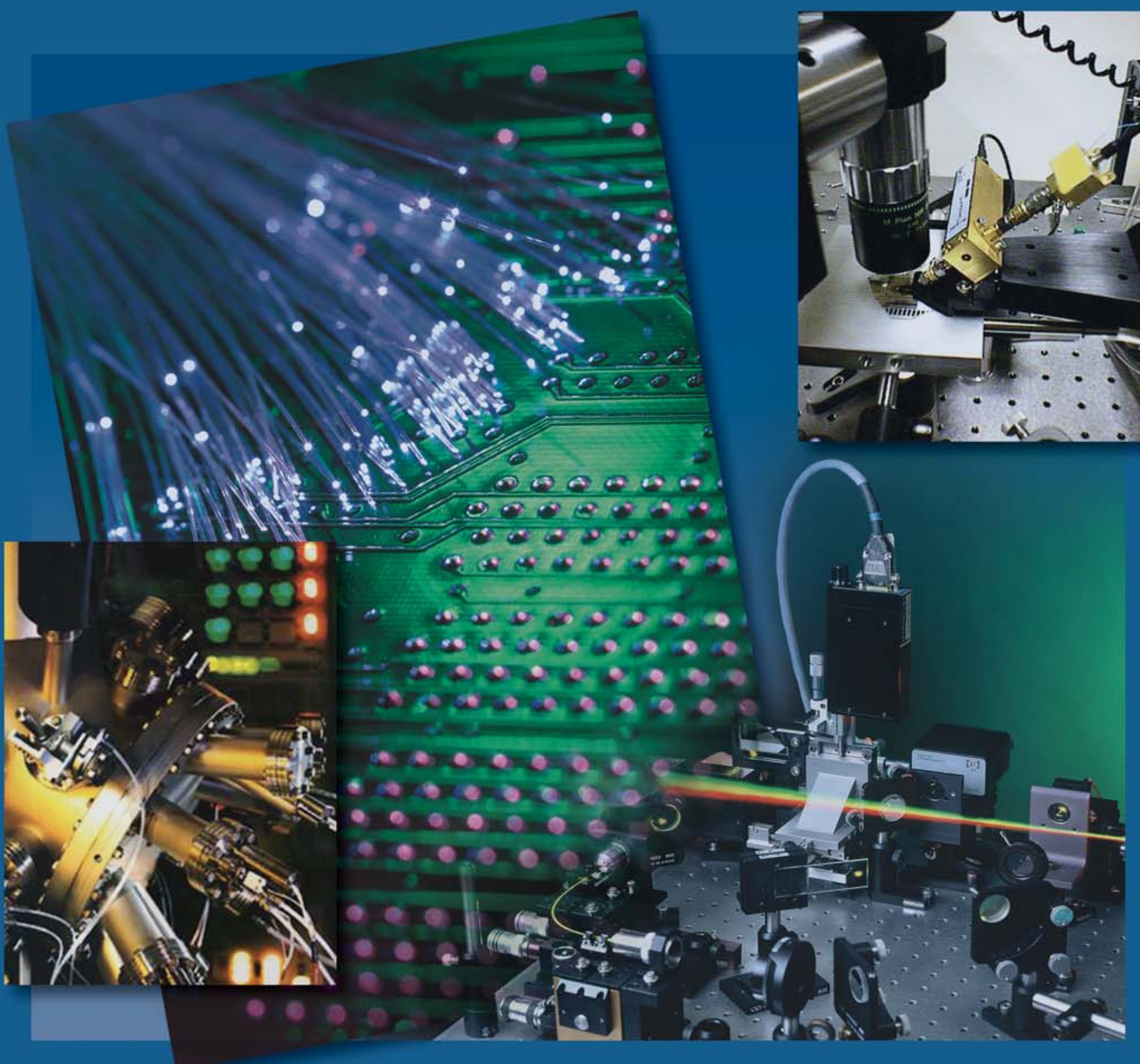
NISTIR 6633

January 2005

Electronics and Electrical Engineering Laboratory

Optoelectronics 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 Optoelectronics 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

Cover caption: On the right are photographs of an apparatus for optically measuring high-speed electrical waveforms and an experiment that generates supercontinuum light from short, intense laser pulses. A photograph of an electrical circuit board and optical fiber is overlaid by vacuum chamber equipment used to grow and fabricate optoelectronic structures. All are examples of the diverse uses and applications of optoelectronics served by the 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
Hratch G. Semerjian, Acting Director

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Contents

From the Division Chief

We are a group of about 60 scientists, engineers, and support staff who work to improve the measurement infrastructure for the optoelectronics industry. Herein, you will find brief descriptions of our program areas and examples of some of our research, development, and metrology goals. More current information is available on our web site. Please contact us if we can be of assistance.

We take metrology seriously. In optoelectronics, as in many other fields, it is a key part of the industrial infrastructure that establishes competitiveness. Consistently specified products are essential in fair trade, and measurements are a key element to efficient manufacturing. The cost of measurements often ranges between 10 % and 30 % of the cost of producing a product. So while the optoelectronics industry, along with many other high technology fields, continues to struggle, advancing the field of optoelectronics metrology remains an important task.

We maintain the U.S. national standards for laser power and energy measurements (see Appendix D) and use them to provide the broadest range of laser calibration capabilities available anywhere. Each year we perform over 200 calibrations of power- or energy-measuring instruments for over 50 customers. We also provide artifact calibration standards, which we call Standard Reference Materials, for over a dozen parameters, most of them related to optical communications. See Appendix E for details. These components provide customers with the capability of performing periodic instrument calibrations traceable to national standards in their own laboratories.

We are developing new tools and techniques for measurements in the rapidly advancing field of nanotechnology. We develop measurement techniques for components and subsystems that can be used online and *in situ* in the manufacture of optoelectronic materials. We perform measurements to provide reference data on the optical properties of important optoelectronic materials. And we work closely with major standards-developing organizations, especially the Telecommunications Industry Association (TIA), the International Electrotechnical Commission (IEC), and the International Organization for Standards (ISO), in producing industry standards.

Our intent is to be the preeminent source of optoelectronics metrology in the world. We strive to provide the best optoelectronic measurement services possible and perform the research and development that best enhances measurement sciences in optoelectronics. If you have any suggestions on how we can improve or how we can serve the industry better, please let me know.

Kent Rochford
Chief, Optoelectronics Division
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About the Optoelectronics Division

Mission

The mission of the Optoelectronics Division is to provide the optoelectronics industry and its suppliers and customers with comprehensive and technically advanced measurement capabilities and standards, and traceability to those standards.

History

The Division is located in Boulder, Colorado, as a part of the NIST Boulder Laboratories. It was established in 1994, succeeding an earlier NIST organizational unit, the Optical Electronic Metrology Group of the Electromagnetic Technology Division. The Division's roots extend to the first NIST (NBS) work on optoelectronics—research begun in the early 1960s to develop techniques for measuring the output power or energy of a laser. Since the late 1960s, NIST research on measurement and standards to support the development and application of lasers has been centered in the Boulder Laboratories. Research related to optical communications was added in the mid-1970s, and expanded substantially in the late 1980s; it now represents more than half of the Division's effort.

Organization

The Division is organized into three Groups. Two Groups—the Sources, Detectors and Displays Group and the Optical Fiber and Components Group—focus on the characterization of optoelectronic components. The third, the Optoelectronic Manufacturing Group, focuses on measurements that can lead to more efficient manufacturing of optoelectronic materials and components.

Research and Services

Most of the research performed in the Division is conducted either with NIST-appropriated funds or under contract to other U.S. government agencies. Results are typically placed in the public domain through publication in the open literature. Some results become the subject of patents, and are available for license. The Division also conducts proprietary research in collaboration with industry and universities through Cooperative Research and Development Agreements (CRADAs).

The Division and its predecessor organizations have been providing calibration services for the characterization of lasers and detectors since 1967, and each year conducts over 200 calibrations for about 50 customers. It also provides the industry with standard reference materials, which are artifact standards that can be used by customers to calibrate their own instrumentation.

The Division maintains close contact with the optoelectronics industry through major industry associations, including the Optoelectronics Industry Development Association (OIDA), the Lasers and Electro-optics Manufacturer's Association (LEOMA), and the Council for Optical Radiation Measurements (CORM). Division staff members represent NIST to the major domestic and international standards organizations active in optoelectronics—the Telecommunications Industries Association (TIA), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the American National Standards Institute (ANSI)—and provide impartial technical expertise in their negotiations.

OPTOELECTRONICS DIVISION STAFF

DIVISION OFFICE 815.00

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McCOLSKEY, Kathy S., Administrative Officer	3288
CASE, William E. (CTR)	3741
MILLS, Maggie, Secretary	3842
NORCROSS, Anna D., Secretary	4384

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KEENAN, Darryl A.	5583
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FRANZEN, Douglas L. (GS)	3346
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WASHBURN, Brian R.(PREP PD)	4447
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ROSENBERG, Danna (DCI PD)	4464
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Legend:

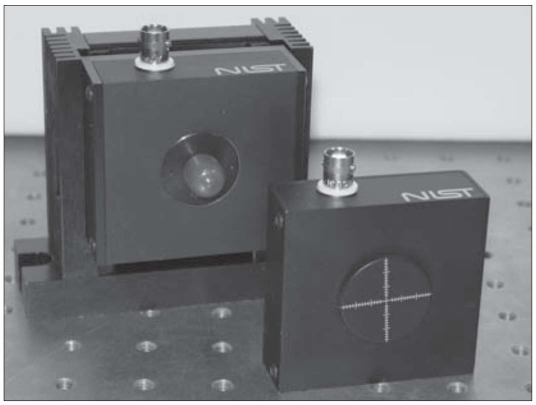
CTR = Contractor
CTR PD = Contractor Post-doctoral
GL = Group Leader
GS = Guest Scientist
PD = Post-doctoral Appointment
PREP PD = PREP Post-doctoral
PL = Project Leader

*Telephone numbers are (303) 497-XXXX, with the four-digit extension given after the name

CW Laser Radiometry

Goals

Develop measurement methods and standards for characterizing laser sources and detectors used with continuous-wave (CW) laser radiation. Develop and maintain measurement services for laser power and energy, optical-fiber power, and related parameters (spectral responsivity, linearity, etc.).



The Optoelectronics Division's Optical Fiber Power Meter transfer standards support measurements over the laser wavelength range from 450 nm to 1800 nm. These detectors have been optimized to provide high-accuracy measurements of optical fiber power and are an essential part of our intramural comparisons for fulfilling the requirements of the NIST Quality System.

Customer Needs

Accurate characterization of optoelectronic sources and detectors is important in the development and use of industrial technologies such as lightwave telecommunications, laser-based medical instrumentation, materials processing, photolithography, data storage, and laser safety equipment. This Project focuses on selected critical parameters intrinsic to sources and detectors, especially the calibration of optical-fiber power meters and laser power or energy meters at commonly used wavelengths and powers or energies. In addition, special test measurements are available for linearity, spectral responsivity, and spatial and angular uniformity of laser power meters and detectors. Project members participate in national and international standards committees developing standards for laser safety, laser radiation, and optical-power-related measurements. They extend and improve source and detector characterizations, including development of low-noise, spectrally flat, highly uniform pyroelectric detectors; high-accuracy transfer standards for optical-fiber and laser power measurements; and advanced laser systems for measurements of laser power and energy.

Technical Strategy

Meeting the needs of the laser and optoelectronics industries and anticipating emerging technologies requires investigation and development of improved measurement methods and instrumentation for high-accuracy laser metrology over a wide range of powers, energies, and wavelengths.

Accuracy of Calibration Services

NIST has historically used electrically calibrated laser calorimeters to provide traceability to the SI units for laser power and energy. In addition, we have a measurement capability based on a Laser-Optimized Cryogenic Radiometer (LOCR), which improves the accuracy of measurement of laser power by an order of magnitude as compared to electrically calibrated radiometers. To meet the increasing demands for higher accuracy over a larger range of optical power and wavelength, it is necessary to improve the accuracy of calibration services through the development of better transfer standards that are traceable to the LOCR.

Standards for Optical Fiber Power Measurements

The continuing development of technology in the telecommunications industry has led to demands for higher performance and higher accuracy for optical-fiber power meter characterization and calibration. In addition, the Department of Defense (DOD) is accelerating the implementation of optical fiber in many of its new weapons systems. By developing improved standards for optical fiber power and by developing instrumentation to accurately quantify the uncertainties of the new standards, we can meet these demanding requirements.

Many new systems being developed for the telecommunications industry demand higher power for optical-fiber power meter (OFPM) characterization and calibration. As much as several watts in fiber is being used in systems to pump laser sources for new applications. We will meet this need by developing the capability to provide calibrations for OFPM up to 10 watts.

Technical Contact:
John H. Lehman

Staff-Years (FY2004):
5 professionals

PLAN: Provide high power capability up to several watts for optical fiber power meter measurements at laser wavelengths of 980 and 1480 nm.

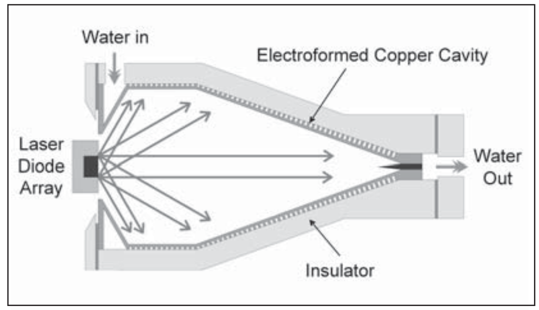
New Coating Technologies for Laser Standards

Single-wall (SWNT) and multiwall (MWNT) carbon nanotubes may form the basis of the next generation of absorber coatings for thermal detectors for high-accuracy optical and thermal radiometry, particularly for high-energy and ultraviolet laser radiometry. Currently, all of the primary standards in the U.S. and elsewhere that are used to establish traceability to SI radiometry units are based on thermal detectors. All of these devices employ some form of thermal absorber coating such as a carbon-based paint or diffuse metal coating (e.g., gold-black). We are developing carbon nanotube coatings for thermal detectors as a highly desirable advance over current state of the art. These coatings must be resistant to damage and aging while maintaining desirable optical and thermal (spectral, spatial, directional uniformity, high thermal conductivity) properties. We have recently demonstrated an optical detector with an absorptive coating consisting of SWNTs.

PLAN: Demonstrate the next generation of coatings for laser power and energy measurement standards based on carbon nanotubes (CNTs). The coatings will allow us to expand existing measurement services to include UV laser measurements and high-power laser diode measurements. Demonstrate thermal detectors suitable for the range of laser wavelengths served by our calibration services (0.157 µm to 10.6 µm).

Characterization of High-Efficiency Diode Sources

We are expanding our calibration services to include measurements of high-efficiency laser diode sources. These measurements include evaluations of the thermal, optical, and electrical properties of the diode sources. We have developed a water-cooled optical radiometer that is capable of accurate optical power measurements up to approximately 100 W. This work supports ongoing developments of high power diode sources for diode-pumped lasers for a variety of applications.

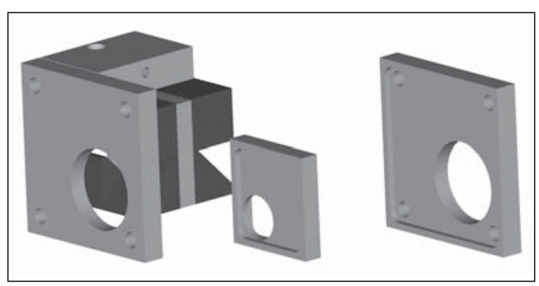


Water-cooled radiometer for measurement of optical output from high-power laser diode arrays. Optical power is converted to heat within the copper cavity. The cavity is cooled with flowing water; the temperature rise of the water is directly proportional to the deposited energy.

Pulsed-to-CW Transfer Standards

There is a need for higher-accuracy calibration of laser-energy meters for pulsed-laser radiation from 3 µJ to 30 mJ with 8 ns to 20 ns pulse-duration, and pulse repetition rates from 1 Hz to 20 Hz. Currently the uncertainty of these measurements using commercially available meters is at the level of 5 % or higher. Traceability through comparisons using the more accurate LOCR are not possible because of the inabilities of existing transfer standards to accurately measure both cw and pulsed laser radiation. Furthermore, there is a need for transfer-standard detectors having wide dynamic range that are insensitive to polarization to have a very low back reflection, and are capable of measurement uncertainty at the 1 % level. We are developing a transfer standard that will provide traceability to both pulsed and cw NIST primary standards (including the LOCR and Q-series calorimeter) for the Army Primary Standards Laboratory (APSL) and Navy Primary Standards Laboratory (NPSL).

PLAN: To reduce, by at least a factor of five, the uncertainty capability of a transfer standard traceable to the LOCR in cw operation, but used normally in measurements involving pulsed laser energy with the Q-series standards. This project is sponsored by the US Army and Navy to improve measurements related to the evaluation of range finders and target designator systems.



A rendered image of the attenuator package for the Pulsed-to-cw transfer standard.

Tunable Solid-State Laser Development

Advances in laser technology are continuously producing lasers with new wavelengths and power levels. We are involved in an ongoing effort to expand wavelength and power-range capabilities through implementation of new tunable solid-state laser technology to keep up with customer needs for calibration services at NIST. These new laser systems will be capable of providing a new wavelength requested by a customer with a minimum of development time and cost by having a flexible suite of laser systems available in the laboratory.

PLAN: Provide calibration services as laser wavelengths at or near 380 nm, traceable to the LOCR. To develop a suite of tunable solid-state lasers to cover the entire spectral range from the deep UV to the thermal IR. This laser system will continue to evolve as new technology becomes available to provide new calibration services as needs arise.

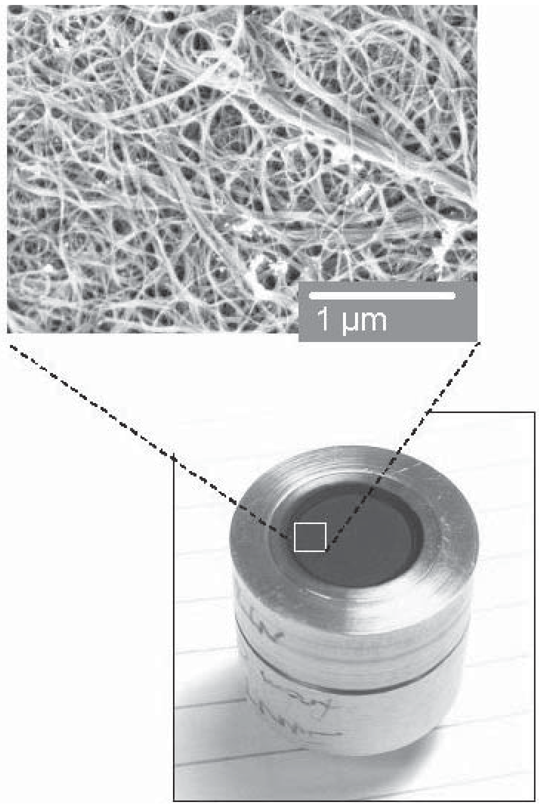
Transfer Standards For Blue/UV Laser Measurements

We have initiated a program to optimize the LOCR and to develop appropriate transfer standards for low-power cw laser measurements at laser wavelengths shorter than 400 nm. Once this program is complete, we will be able to provide traceability for optical detectors used in the calibration of instrumentation used for detection of chemical and biological aerosols.

PLAN: Pursue new technologies to improve our measurement capability, including improved transfer standards, improved coatings for thermal detectors, and optimization of the LOCR for blue and UV laser power measurement traceablility.

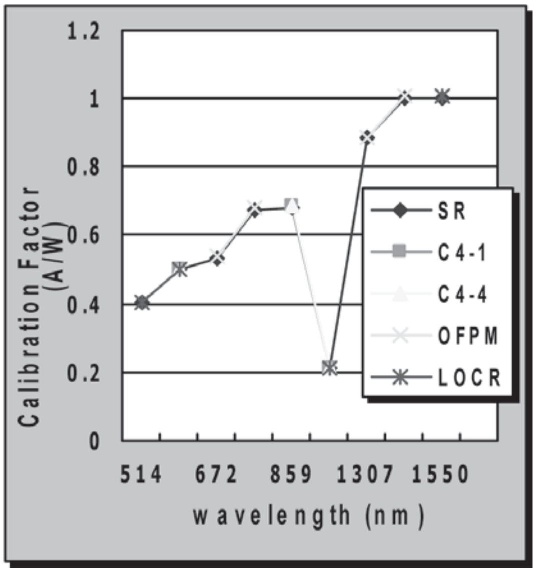
Accomplishments

■ We have evaluated a bulk form of single-wall carbon nanotubes (SWNTs) as a coating for future optical standards. Several features of the SWNT coatings are apparent from the measurements. The absorption efficiency of SWNT coatings is greater than that which was expected for the bare (uncoated) detector. Furthermore, the detector's response (and hence the absorption of the SWNT coatings) varies by less than 5 percent as a function of wavelength from 600 nm to 1550 nm. The nanotube-based coatings do not compromise the detector performance. These encouraging results indicate that once an optimized SWNT coating has been achieved, the expected detector responsivity of a SWNT-coated standard should surpass the performance of current gold-black coated standards. The resulting SWNT-coated detector will be a more robust, spectrally flat optical standard.



Pyroelectric detector coated with single-wall carbon nanotubes and imaged by means of a scanning electron microscope (inset).

■ We also completed intramural comparison of NIST laser and optical fiber power calibration services. The comparison demonstrated the equivalence of absolute responsivity as provided by NIST calibration services at laser wavelengths of 633, 850, 1060, 1310, and 1550 nm by use of NIST check standards. The results indicated that the responsivity of the check standards, as determined independently by the various calibration services, agreed to within the published expanded uncertainties ranging from 0.02 % to 1.24 %.



Summary of absolute responsivity values for NIST intramural comparison. Data were accumulated from four calibration services: spectral responsivity (SR), low-level cw (C4-1 and C4-4), optical fiber power (OFPM), and the high-accuracy laser power and energy (LOCR).

■ We demonstrated that the accuracy of optical-fiber power measurements depends on the type and manufacturer of the fiber connector. A comparison of absolute responsivity measurement results for four different optical-fiber power meter standards at 850 nm, 1310 nm and 1550 nm for five different types of fiber connectors (FC, ST, biconic, SC, and SMA) produced by three different manufacturers yielded reproducible offsets in detector calibration factors due to fiber connector types as large as 4.6 %.

Calibrations

The Optoelectronics Division provides calibration services for laser and optical-fiber power at many wavelengths and power levels from the ultraviolet and far-IR spectral regions, and from picowatt to kilowatt power levels. See Appendix D for a list of available calibrations. The Division can also provide special tests for other wavelengths and powers upon request.

Standards Committee Participation

American National Standards Institute: John H. Lehman is a member of committee Z136, subcommittees SSC-01 and SSC-04, which deal with Safe Use of Lasers.

Telecommunications Industry Association: Igor Vayshenker is a member of subcommittee FO-4.9, which deals with Metrology and Calibration.

Recent Publications

J. H. Lehman, A.C. Dillon, C. Engtrakul, "Carbon nanotubes based coatings for laser power and energy measurements using thermal detectors," *Conference on Lasers and Electro-Optics*, *OSA Technical Digest* (Optical Society of America, Washington DC) (2004).

J.H. Lehman, I. Vayshenker, D.J. Livigni, J. Hadler, "Intramural comparison of NIST laser and optical fiber power calibrations," *J. Res. Natl. Inst. Stand. Technol.* 109, 291-298 (2004).

D.L. Livigni, "High accuracy laser power and energy meter calibration service," *NIST Spec. Publ.* 250-62 (2003).

J.H. Lehman and C. Pannell, "Position and temperature dependence of pyroelectricity in domain-engineered stoichiometric and congruent LiTaO3," *Ferroelectrics*, 296, 39 – 55, (2003).

J.H. Lehman, E. Theocharous, G. Eppeldauer, C. Pannell, "Gold-black coatings for freestanding pyroelectric detectors," *Meas. Sci. Technol*., 14, 916 – 922, (2003).

I. Vayshenker, H. Haars, X. Li, J. H. Lehman, and D. J. Livigni, "Optical-Fiber Power Meter Comparison Between NIST and PTB," *J. Res. Natl. Inst. Stand. Technol.* 108, 391-394 (2003)

J.H. Lehman and C.L. Cromer, "Optical Trap Detector for Calibration of Optical Fiber Power Meters: Coupling Efficiency," *Appl. Opt*., Vol. 41, No. 31, pp. 6531-6536 (2002).

J.H. Lehman, A.M. Radojevic and R.M. Osgood Jr., "Domain-Engineered Thin-Film LiNbO3 Pyroelectric-Bicell Optical Detector," *IEEE Phot. Tech. Lett*., Vol. 13, pp. 851-853 (2001).

Pulsed-Laser Radiometry

Goals

Develop measurement methods and standards for characterizing pulsed-laser sources and detectors. There is ongoing development work in the following areas: standards development, calibration services, and advising customers on in-house measurements.

Customer Needs

Accurate measurement methods and standards for characterizing pulsed-laser sources and detectors are critical in a number of industrial applications. Project members work closely with industry to develop standards, new technology, and appropriate measurement techniques for pulsed-laser measurements. These efforts include development work in standard detectors, calibration services, and advising customers on in-house measurement capabilities. The bulk of our work is concentrated on laser metrology using ultraviolet (UV) excimer lasers and infrared (IR) Q-switched lasers.

Excimer lasers are used in a wide range of industrial applications. Excimer lasers are used in corneal sculpting procedures for vision correction, for example, in photorefractive keratectomy (PRK) and Laser In-situ Keratomileusis (LASIK), as well as in micromachining of small structures such as inkjet printer nozzles. However, the bulk of our efforts are concentrated on UV laser metrology in support of optical lithography for semiconductor manufacturing.

Increasing information technology requirements have yielded a strong demand for faster logic circuits and higher-density memory chips. This demand has led to the introduction of deep-ultraviolet (DUV) laser-based lithographic tools for semiconductor manufacturing. These tools, which employ KrF (248 nm) and ArF (193 nm) excimer lasers, have led to an increased demand for accurate laser measurements at the DUV laser wavelengths. As a result, NIST, with International SEMATECH support, has developed primary standard calorimeters for measurements of laser power and energy at excimer laser wavelengths of 157, 193, and 248 nm.

Q-switched IR lasers are used in many industrial applications, such as metal fabrication, cutting, and welding. In addition, these lasers are used in military settings for target designation and range finding.

Technical Strategy

We work closely with our calibration customers and research sponsors to identify key areas for improvement and research.

Excimer Laser Metrology

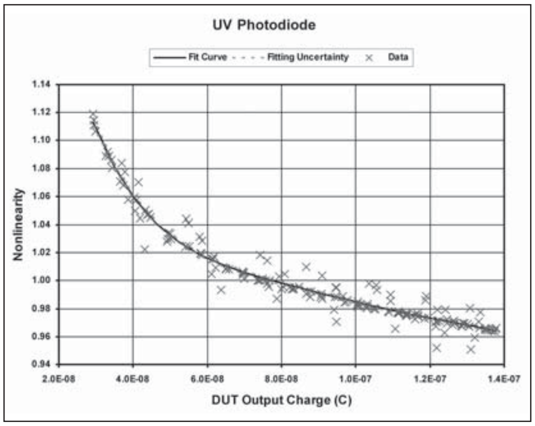
Beginning with the first edition of the National Technology Roadmap for Semiconductors in 1992, the semiconductor industry has made an organized, concerted effort to reduce the feature sizes of integrated circuits. As a result, there has been a continual shift towards shorter exposure wavelengths in the optical lithography process. Because of their inherent characteristics, DUV lasers, specifically KrF (248 nm) and ArF (193 nm), and more recently F_2 (157 nm) excimer lasers, are the preferred sources for high-resolution lithography at this time.

PLAN: Provide timely, accurate calibrations traceable to SI units for customers at 248 nm, 193 nm, and 157 nm.

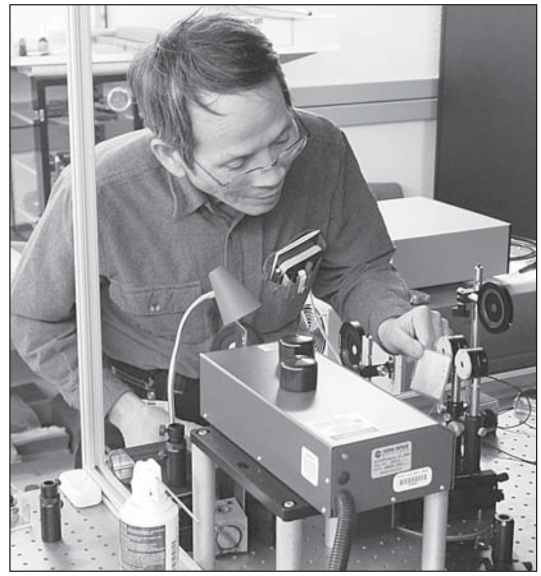
The excimer laser calibration services use electrical-substitution calorimeters as primary standards to provide direct traceability to SI units for laser power and energy measurements. Calorimeters, while having the advantage of providing the highest level of accuracy for these measurements, have a slow response time. Therefore, because calorimeter-based calibrations are both time-consuming and expensive, typically only a few calibration points are measured. However, most laser detectors are typically used over a range larger than that covered by a single calibration point. As a result, additional measurement uncertainty will be introduced if the detector response is not linear and the nonlinearity is not quantified. Range discontinuity, *e.g.*, change in response due to a nonlinear change in detector amplification, can also introduce additional measurement uncertainty. Measurements of detector nonlinearity and range discontinuity will give complete information of the detector's response over the entire measurement range, with the added benefit that the measurement technique is much faster, and therefore cost is much less compared to adding more calibration points.

Technical Contact:
Christopher Cromer

Staff-Years (FY2004):
4 professionals



Relative response of a typical UV laser energy detector as a function of measured output charge illustrating how nonlinear response can degrade the accuracy of calibrations performed on this type of detector.



The quality of our calibrations services depends on the excellence of our staff. Here, Xiaoyu Li aligns optics in preparation for a customer calibration.

Metrology for Eye-Safe Laser Target Systems

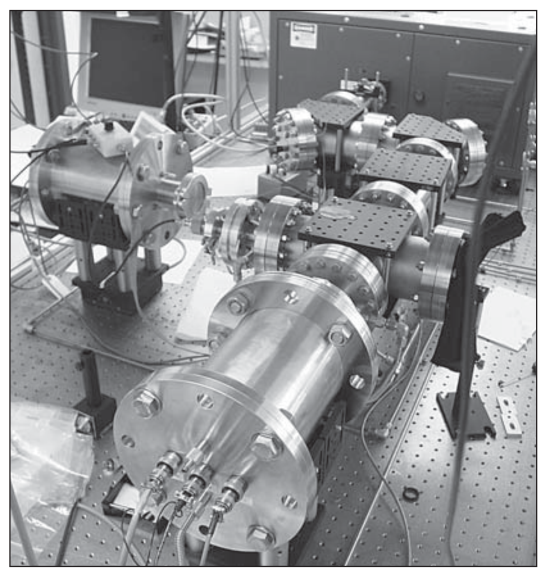
Recently there has been increasing demand to extend the wavelength range of laser target ranging and designation systems to the eye-safe laser regime. These laser systems provide positional information, such as distance and incident angle, for use in locating targets. There is a need to extend existing pulsed Nd:YAG laser power and energy calibration services to include measurements at 1.55 µm and to reduce the overall uncertainty associated with these measurements. In addition, there is need for high-power attenuators both at 1 µm and 1.5 µm. Commercially available laser attenuators do not have the required durability and linearity when used with the hundreds of millijoules from these high-power Q-switched lasers.

PLAN: Develop capabilities for measurements of high pulse energy at 1.5 µm. Design, build, and characterize an improved calibration service for measurements of attenuators for use with Q-switched Nd:YAG lasers.

Accomplishments

■ Completed the testing of the system for characterizing detector nonlinearities at 193 nm. This versatile system can be used to characterize a wide range of UV detectors and has generated interest among detector manufacturers and International SEMATECH. This service may be an inexpensive alternative to customers who are more concerned with the relative, rather than the absolute, response of their detectors. The primary reason for its lower cost is the reduced turnaround time; a measurement of linearity takes only one-third the time of a full calibration.

■ Completed construction of an excimer laser calibration system for detector calibrations at 157 nm. We have completed three calibrations for customers using this new measurement system. Demand for the 157-nm calibration service exists despite the decision of SEMATECH to abandon their 157-nm photolithography program.



The 157-nm calibration system uses high vacuum parts to ensure an oxygen-free environment. As little as 1 ppm of oxygen can severely impact calibration quality. The 157-nm primary standard is in the foreground and the 157-nm excimer laser is in the background.

■ As part of our quality system, we have completed an internal comparison of all three calorimeters used for excimer laser energy measurements at 157 nm, 193 nm, and 248 nm. The comparisons at 193 nm and 248 nm all show agreement to better than 0.3 %.

■ Completed design and testing of updated control electronics for the Q-series calorimeters. The new controllers include improved stability and lower noise. We have begun maintenance on three laser calorimeters belonging to the Air Force, which are based on our Q-series laser calorimeters. The Air Force calorimeters were built approximately 20 years ago, and are being refitted with the new control electronics. Each calorimeter will be upgraded and returned in series, so the AF calibrations lab will have at least two on hand to handle calibration workloads.

Calibrations

The Pulsed-Laser Radiometry Project provides pulsed-laser calibration services for laser power and energy using excimer and pulsed-Nd:YAG lasers. See Appendix D for a complete list of available wavelengths and laser power/energy ranges.

Standards Committee Participation

International Standards Organization: Marla L. Dowell is a member of working group TC 172/SC 9/WC 1, which deals with terminology and test methods for lasers.

American National Standards Institute: John H. Lehman is a member of committee Z136, subcommittees SSC-01 and SSC-04, which deal with safe use and measurement of lasers.

U.S. National Committee/International Electrotechnical Commission: John H. Lehman is a member of technical committee TC76, working groups 1 and 3, which deal with laser radiation measurement and safety.

Recent Publications

H. Laabs, D. A. Keenan, S. Yang, and M. L. Dowell, "Measurement of Detector Nonlinearity at 193 nm," accepted for publication in Applied Optics.

C. L. Cromer, M. L. Dowell, R. D. Jones, D. A. Keenan, and S. Yang, "A Primary Standard for 157 nm Excimer Laser Measurements," in *AIP Conf. Proc., Characterization and Metrology for ULSI Tech. 2003*, No. 683, 409-412 (2003).

S. Yang, D. A. Keenan, H. Laabs, M. L. Dowell, "A 193 nm Detector Nonlinearity Measurement System at NIST," *Proc., SPIE, Optical Microlithography XVI*, Vol. 5040, pp. 1651-1656, (2003).

H. Laabs, R. D. Jones, C. L. Cromer, M. L. Dowell, V. Liberman, "Damage Testing of Partial Reflectors for 157 nm Laser Calorimeters," *Proc., SPIE, Laser-Induced Damage in Optical Materials 2001*, Vol. 4679, 332-338 (2002).

M. L. Dowell, C. L. Cromer, R. D. Jones, D. A. Keenan, and T. R. Scott, "New Developments in Deep Ultraviolet Laser Metrology for Photolithography," in *AIP Conf. Proc., Characterization and Metrology for ULSI Tech: 2001*, No. 550, 361-363 (2001).

M. L. Dowell, "Choosing the Right Detector is Key to Accurate Beam Power Measurements," *OE Magazine*, 56 (January 2001).

High-Speed Measurements

Technical Contact:
Paul Hale

Staff-Years (FY2004):
3 professionals

Goals

Provide advanced metrology, standards and measurement services relating to temporal properties of optical sources, detectors, and signals used in association with optoelectronic systems.

The electro-optic measurement system, shown here being operated by Tracy Clement, measures an electrical pulse on a $LiTaO_3$ wafer. De-embedding techniques are then used to determine the voltage generated by the photodiode being tested at its coaxial output connector. (© Geoffrey Wheeler)

Customer Needs

High-bandwidth measurements are needed to support systems that take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5–10 gigabits per second using time-division multiplexing (TDM). Research is being done on the next generation of TDM systems at 40 gigabits per second and higher in laboratories around the world. Methods are needed to accurately characterize the scalar and vector frequency response of high-speed sources, detectors, and instrumentation to three to ten times the system modulation rate. Burst-mode operation in asynchronous transfer mode networks requires additional characterization at very low frequencies. Increasingly tight tolerances in both digital and analog systems require both frequency- and time-domain measurements with low uncertainty.

The intensive use of laser target designators and range finders by the armed forces requires traceable calibration standards for low-level peak pulse power and energy at 1064 nm and 1550 nm.

Technical Strategy

We have developed a suite of highly accurate measurement systems for characterizing high-speed optoelectronic and microwave devices.

Optoelectronic Vector Frequency Response Measurements to 110 GHz

NIST has developed highly accurate heterodyne techniques at 1319 nm and 1550 nm for measuring the scalar frequency response of detectors. Measurement services are available for modulation frequency-response transfer standards that consist of a photodiode combined with a microwave power sensor, and can measure this type of standard from 300 kHz to 110 GHz or more at 1319 nm. We also have a service for calibrating the frequency-response magnitude of bare photodiodes to at least 50 GHz. Calibration of bare photodiodes is more complicated because it requires calibrated microwave power and scattering-parameter measurements.

Optoelectronic phase response, when combined with the magnitude response, is called the vector response. The vector frequency response of a photoreceiver is the Fourier transform of its impulse response. Vector response is required for the design of high-speed optoelectronic systems, but until recently there were no accepted standard methods for this measurement.

Researchers in the High-Speed Measurements Project have demonstrated time-domain techniques for measuring optoelectronic vector response with verifiable accuracy up to 110 GHz using electro-optic sampling (EOS). By developing these measurements our project is pioneering a new paradigm for time-domain measurements with frequency-domain calibrations.

PLAN: Extend EOS capability to 200 GHz by use of on-wafer measurement techniques.

Applications of Optoelectronic Measurements

Optical communications analyzers and reference receivers used for measuring digital eye-patterns on optical signals have many similarities to electrical oscilloscopes, but also have advantages of their own. In particular, they can be calibrated over a very high bandwidth because they do not require band-limited microwave calibrations.

Calibrated time-domain measurements, however, possess some unique problems. For example, we must develop methods for removing time-base distortions and deconvolving the oscilloscope response and impedance mismatch. Point-by-point uncertainty analysis in the time domain will enable industry to improve eye-pattern measurements and to quantify the performance of bit-error-ratio testers.

Commercial equipment presently available for characterizing the phase dispersion and phase delay of optoelectronic receivers suffers from high uncertainty, limited bandwidth, and in some cases, unverified calibrations, or calibrations that are not traceable to fundamental physical principles. Traceable vector frequency-response measurements are critical for characterizing balanced receivers that are needed for coherent optical communication applications.

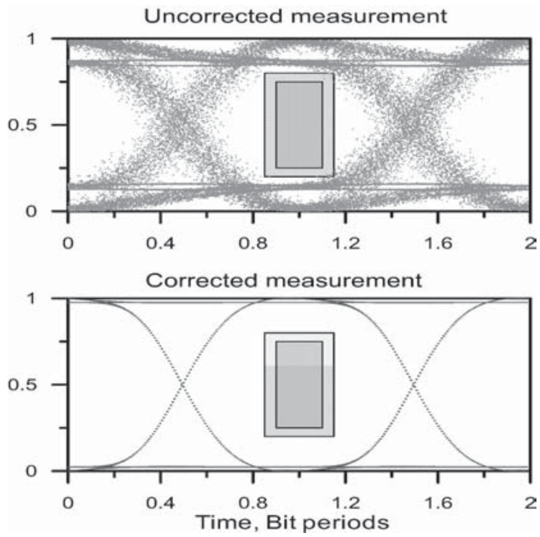
PLAN: Provide calibrated pulse sources for instrumentation and component manufacturers that are traceable to fundamental units. Establish oscilloscope calibration services that are traceable to the EOS system.

Waveform Metrology

High-speed/high-bandwidth waveforms contain valuable information missed by current electronic measurement techniques that could be captured with new optoelectronic-based metrology. Waveform measurements verify signal fidelity and standard compliance for the design and qualification of components and systems. Yet current waveform test equipment is characterized only with single-parameter metrics, such as bandwidth or rise-time. Common equipment properties, such as loss, mismatch, modulation response, and jitter, which become significant above a few gigahertz, are typically not corrected or characterized. In many cases, these limitations on waveform measurement equipment arise from a lack of comprehensive metrology.

We will develop fundamentally new techniques and measurement services, at bandwidths and rise-times currently unattainable, to verify waveforms for a wide range of applications (*e.g.*, optical communications, high-speed microcircuitry, wireless communication, advanced radar, and remote sensing). This metrology will generate significant savings in production costs stemming from false rejections of functioning devices due to inaccurate signal characterization.

PLAN: Develop accurate measurements of pattern dependent jitter, time delay, and signal integrity.



Simulated eye mask test of a long random bit sequence transmitted by a fiber-optic transceiver. The forbidden region in this pass/fail test is shown in the hashed region, surrounded by a 10 % guard band (margin). Although the simulated transceiver meets specifications, the frequency response and jitter errors in the oscilloscope measurement (top) cause the transceiver to fail the test as some samples fall into the guard band. The bottom graph shows the effect of calibrating and correcting the oscilloscope errors, clearly passing a $1,000 component that would otherwise have been rejected.

Metrology for Eye-Safe Laser Target Systems

Military systems involving laser trackers and target designators are converting to and/or adding a capability to operate at laser wavelengths of 1.5 µm because of the eye-safe benefits. However, there are no commercial standards for measuring low-levels of pulsed laser power/energy in this wavelength region. Currently, pulsed laser standards are silicon-based and do not operate at wavelengths longer than 1.1 µm in the infrared, requiring the development of new instrumentation. We are developing new transfer standards, as well as the systems to calibrate them, capable of low-level pulsed power/energy laser measurement in the 1.5 µm wavelength region. These standards will be transitioned to meet Homeland Security requirements and military systems certification. Calibrations will be traceable to national laser power/energy standards and supported by NIST.

PLAN: Demonstrate improved 1.5 µm calibration capability with accuracy and ease of operation comparable to previous 1.06 µm system. Provide customers with the capability to deconvolve radiometer impulse response for arbitrary pulse shapes.

ACCOMPLISHMENTS

Recent advances in high-speed measurements have been a result of close collaborations with the Electromagnetic Division (EEEL) and with the Statistical Engineering and the Numerical and Computational Sciences Divisions (ITL).

■ Developed an electro-optic sampling system to sample high-speed electrical waveforms on a coplanar waveguide with ultrashort laser pulses via the electro-optic effect. Standard microwave techniques are used to calibrate the response of a photoreceiver at its 1 mm electrical port that is physically removed from the sampling plane.

■ Accurately characterized the modulation response magnitude and phase of commercially available photoreceivers to 110 GHz, nearly three times the bit rate of 40 Gb/s optoelectronic systems. The frequency range of the calibration is limited only by the 1 mm coaxial connectors. The characterized photoreceiver has a bandwidth of about 80 GHz; the signal-to-noise ratio of the measurement is greater than 150:1 at 110 GHz.

■ To facilitate on-wafer waveform measurements, we implemented a new slotted-line technique that uses electro-optic sampling to measure the impedance of coplanar waveguide terminations. This method has the advantage that it can be used to measure impedance into the terahertz range.

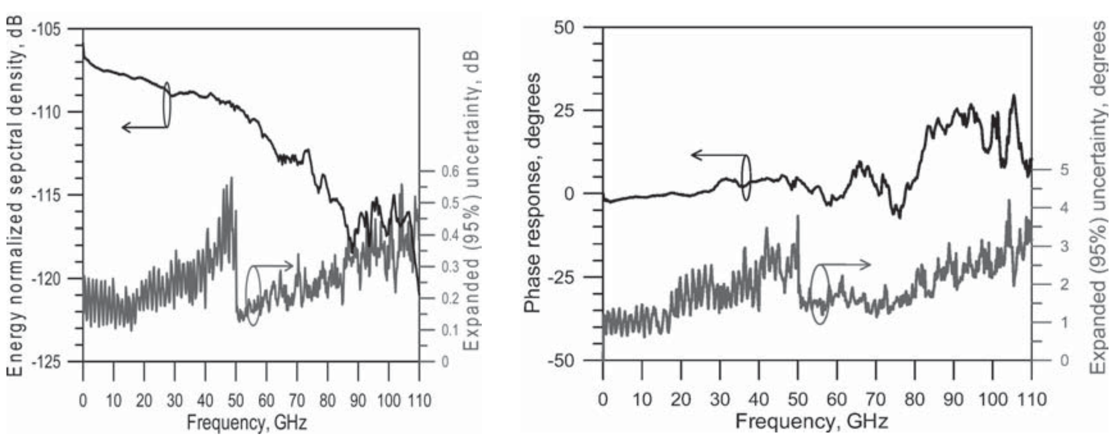
■ In conjunction with the slotted-line impedance measurement, we demonstrated a calibrated on-wafer waveform measurement over a 200 GHz frequency range, with a point-by-point time-domain uncertainty analysis. Since the frequency range of this measurement was limited only by the bandwidth of the photodiode we used as an electrical pulse generator, we can potentially make calibrated waveform measurements into the terahertz regime, *i.e.*, to pulse widths of less than 1 ps.

■ Described, in the open literature, a rigorous theory for calibrating the small-signal optoelectronic frequency response of photoreceivers and modulated sources when using an electrical vector network analyzer. Previous theories did not consider effects of optical coherence on such measurements, and this work describes how coherence effects can be avoided to give more accurate measurements.

■ Established sampling oscilloscope calibration capability, traceable to EOS, with full uncertainty analysis. This capability is now available as a Special Test for both internal and external customers.

MEASUREMENT SERVICES

The Optoelectronics Division provides measurement services relating the temporal properties of optical sources and detectors used with optoelectronic systems, including optical receiver frequency response (scalar or vector), impulse response, and low-level pulse power and energy. For more information see Appendix D or contact Paul Hale at (303) 497-5367.



Electro-optic sampling is capable of determining the vector frequency response of a photodiode, that is, it can determine both the magnitude and phase response of the photodiode.

Standards Committee Participation

International Electrotechnical Commission: Paul Hale is a member of technical committee TC86, working group 4, which deals with Fiber Optic Test Equipment Calibration.

International Telecommunication Union: Paul Hale is a technical correspondent for ITU-T Study Group 4 working on recommendations for instrumentation measuring jitter and wander in synchronous digital hierarchy (SDH) equipment.

Recent Publications

D. F. Wiliams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Calibrated 200 GHz waveform measurement," accepted for publication, *IEEE Trans. Microwave Theory Tech.*

K. J. Coakley, C. M. Wang, P. D. Hale, and T. S. Clement, "Adaptive characterization of jitter noise in sampled high-speed signals," *IEEE Trans. Instrum. Meas.*, Vol. 52, pp.1537-1547 (Oct. 2003).

P. D. Hale and D. F. Williams, "Calibrated measurement of optoelectronic frequency response," *IEEE Trans. Microwave Theory Tech.*, Vol. 51, pp.1411-1429 (April 2003).

T. S. Clement, D. F. Williams, P. D. Hale, and J. M. Morgan, "Calibrating photoreceiver response to 110 GHz," *IEEE Lasers and Electro-optics Society Annual Meeting Digest*, pp.877-878 (Nov. 2002).

T. S. Clement, P. D. Hale, P. A. Williams, "Tutorial: Fiber and Component Metrology for High-Speed Communication," *Proc., Optical Fiber Communication Conf.*, March 17-22, 2002, Anaheim, CA, WZ1 (March 2002).

C. W. Wang, P. D. Hale, K. J. Coakley, and T. S. Clement, "Uncertainty of Oscilloscope Timebase Distortion Estimate," *IEEE Trans. Instrum. Meas.*, 51, 53-58 (Feb. 2002).

T. S. Clement, S. A. Diddams, and D. J. Jones, "Lasers, Ultrafast Pulse Technology," *Encycl. Phys. Sci. Tech. Third Edition*, Vol. 8, 499-510 (Jan. 2001).

P. D. Hale, T. S. Clement, D. F. Williams, E. Balta, N. D. Taneja, "Measuring the Frequency Response of Gigabit Chip Photodiodes," *IEEE J. Lightwave Technol.* **19**: 1333-1339 (Sept. 2001).

D. F. Williams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Calibrating Electro-Optic Sampling Systems," *Proc., Intl. Microwave Symposium*, May 20-25, 2001, Phoenix, AZ, 1527-1530 (May 2001).

P. D. Hale, T. S. Clement, and D. F. Williams, "Frequency Response Metrology for High-Speed Optical Receivers," *Tech. Dig., Optical Fiber Communication Conf. (OFC'01)*, March 17-22, 2001, Anaheim, CA, WQ1-1-3 (March 2001).

K. J. Coakley and P. D. Hale, "Alignment of Noisy Signals," *IEEE Trans. Instrum. Meas.*, **50**: 141-149 (Feb. 2001).

R. W. Leonhardt, "Calibration Service for Low-level Pulsed-laser Radiometers at 1.06 µm: Pulse Energy and Peak Power," *NIST Special Publication 250-64* (2004).

P. Bryant, J. Grigor, P. Harris, B. Rich, A. Irwin, S. McHugh, D. W. King, and R. W. Leonhardt, "Advanced Test and Calibration Systems for Integrated Multi-Sensor Platforms with IR, Visible, and Laser Range Finder/ Designator Capabilities," *Proc., SPIE, Vol. 5076, The International Society for Optical Engineering, Infrared Imaging Systems: Design, Analysis Modeling and Testing XIV* (April 2003).

Display Metrology

Technical Contact:
Paul Boynton

Staff-Years (FY2004):
3 professionals

Goals

Television, computers, and telecommunications are merging into advanced digital video and computer systems that will provide new services for education, engineering, manufacturing, robotics, entertainment, medicine, defense, security, transportation, publishing, advertising, banking, and government. A critical element in this convergence is that electronic displays are becoming ubiquitous. Although displays are manufactured primarily offshore, U.S. manufacturers are the largest consumer of displays. To facilitate worldwide commerce in displays, a well-defined method for specification and verification of display quality is needed to ensure that the display will work under the necessary lighting conditions. NIST is working with industry standards-developing organizations to ensure such equity in the marketplace by developing the metrology base for displays.

Customer Needs

The United States is a major buyer of electronic displays for computer, consumer, automotive, medical, telemedicine, and avionics use. Sound metrology is urgently needed in this highly competitive environment of new and emerging display technologies. Further, a universally recognized and accepted document is needed to provide customers with a tool to use in choosing the best display for their application.

Technical Strategy

This project is concerned with display metrology in general and involves numerous ongoing tasks. However, we focus our research on specific issues identified by industry as particularly important.

Refinement of Measurement Procedures

We are developing and refining measurement procedures in support of ongoing electronic display metrology, and applying the results in the development of national and international standards for characterization of flat panel displays.

PLAN: To support the revision of the Video Electronics Standards Association (VESA) Flat Panel Display Measurement Standard (FPDM) through the development of measurement methods and written standards.

Characterization of Reflection Components

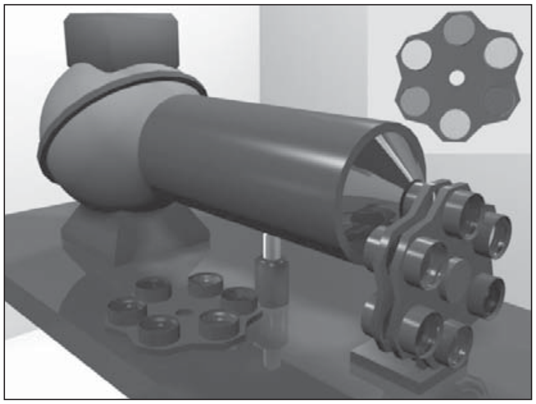
The characterization of the three components of reflection (Lambertian, specular, and haze) associated with displays is being developed. Development and implementation of robust methods is needed to characterize display reflection performance under actual conditions, *e.g.*, the readability of automotive displays in high ambient light conditions.

PLAN: To analyze and publish the success of our variable-radius-source method is in capturing the specular component and haze peak in making robust reflection measurements. (This is a collaborative effort with NIST's Optical Technology Division).

New Interlaboratory Comparison Standards

To determine the measurement capabilities of participating laboratories in an interlaboratory comparison effort, this project has developed a multi-filter source-display measurement assessment transfer standard (DMATS) that can be shared among participating laboratories. The combination of all the targets will provide a benchmark of the capabilities of participating laboratories in making conventional luminance and color measurement. Typically, light-source calibrations involve only a white point. These new standards include the white point and much of the color gamut. A simplified version of this apparatus employing filter wheels instead of a filter array has been developed. This apparatus is referred to as the gamut assessment standard (GAS). The DMATS/GAS solution is essential to resolving issues of color transportability in E- commerce by assuring that the color measurement instrumentation employed is sufficiently reliable to discriminate color differences. This program is conducted in collaboration with the Physics Laboratory's Optical Technology Division.

PLAN: Investigate the design of a robust light source for using in the gamut assessment standard (GAS) and conduct general interlaboratory comparisons on a regular basis with industry.



Gamut Assessment Standard (GAS).

Liquid-Filled Camera Project

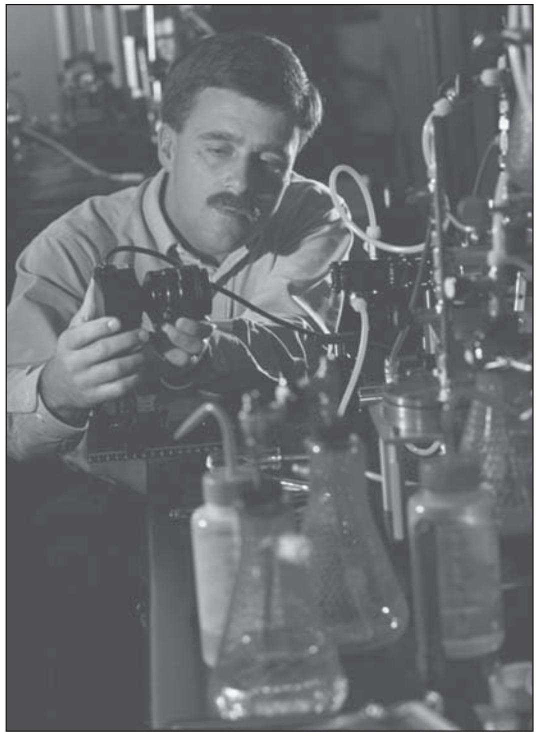
In order to reduce stray-light contributions to the reference image and enable more accurate luminance measurements of complicated scenes involving high contrasts, a liquid-filled camera is under development that simulates the optics of the human eye.

PLAN: Investigate the use of the eyeball-like camera to accurately measure near-eye displays.

Dissemination of Information

A key component of our work is in the education of our customers. We seek to provide our customers with the information that they need through standards activities, conference presentations, invited tutorials, and publications. As a part of this effort, we are developing a one-week hands-on course on good display metrology practices. This course will be offered on an ongoing basis at the NIST-Boulder campus.

PLAN: Prepare an in-house course on display metrology that provides hands-on laboratory measurements. We plan to teach the in-house course on display metrology at least once each year up to four times per year.



NIST Researcher Paul Boynton adjusts camera to evaluate forward scattering in fluid used in liquid-filled camera.

Accomplishments

■ Test patterns with synthetic faces were developed for the digital cinema industry in collaboration with Digital Cinema Initiatives, Inc. These faces take advantage of human acuity to slight variations in facial features and are used in a variety of patterns to assist in set-up and evaluation of displays.

Synthetic faces used to evaluate display quality.

■ The gamut assessment standard (GAS) was calibrated and made ready for beta testing with participating laboratories.

■ Two invited seminars on Flat Panel Display Measurements and Standards were presented: one at the Society for Information Display (SID) 2004 International Symposium and the other at the SID Asia Display Conference. These seminars were well attended (approximately 300 people at the SID, a little fewer at Asia Display) Emphasis was placed on (1) techniques being as important as good equipment and (2) reflection metrology is more complicated than currently envisioned by the display industry.

- A draft of the ISO 9241 Ergonomic requirements and measurement techniques for electronic visual displays — Part 302: Terminology and Part 305: Optical laboratory test methods were approved for DIS circulation. Kelley and Boynton serve as project editors for Part 302 and Part 305, respectively, for this standard.

Collaborations

In addition to the collaborations that follow naturally from standards activities (see below) and other routine advisory roles, there are some specific collaborations of interest that are currently underway:

Several test patterns were developed, including some with synthetic faces, for the digital cinema industry in collaboration with Digital Cinema Initiatives, Inc, a consortium of major motion-picture studios and other industry-related companies.

We are working with the Food and Drug Administration (FDA) on making small-area measurements of radiological images using stray-light-reducing probes for small-area measurements of luminance.

Robust and meaningful reflection measurements of organic light-emitting displays (OLEDS) are being developed with DuPont Displays.

Standards Committee Participation

Video Electronic Standards Association (VESA) Display Metrology Task Group: E. F. Kelley, former chair of this group, currently serves as editor of the Flat Panel Display Measurement (FPDM) Standard, a scientific and comprehensive document, prepared with significant input from NIST, to address display metrology. Kelley is responsible for creating and implementing all of the patterns used by the standard in addition to his editorial responsibilities for the next generation document (FPDM3) and associated measurement methods.

International Organization for Standardization TC159/SC4/WG2 Visual Display Requirements: P. A. Boynton is a member of this committee, which is developing a revision of all of its display standards. NIST is coordinating the development and evaluation of the metrology sections.

International Electrotechnical Commission TC 110/ PT 62341-6: Organic Electroluminescent Displays - Part 6: Measuring Methods of Organic Light-Emitting Displays. P. A. Boynton is providing technical expertise in the development of this standard.

Society for Automotive Engineers J 1757 Standard Metrology for Vehicular Flat Panel Displays: E. F. Kelley is a member and is providing support in the evaluation of reflection measurements and developing appropriate efficiency metrics.

Council for Optical Radiation Measurements CR-5 (Flat Panel Displays). All project personnel are members. J. M. Libert is working with the committee to evaluate the DMATS and GAS program.

Recent Publications

E. F. Kelley and P. A. Boynton, "Seamless Frusta Creation for Stray-Light Management in Optical Devices," NISTIR to be published in October 2004.

E. F. Kelley, "What Do the Specifications Mean?," *SID Americas First Display Engineering and Applications Conference*, Ft. Worth, TX. To be published October 2004.

P. Boynton, "Tools and Diagnostics to Assess and Improve Projection Display Metrology Capabilities," *SID Americas First Display Engineering and Applications Conference*, Ft. Worth, TX. To be published October 2004.

E. F. Kelley, "Flat-Panel-Display Measurement Techniques and Concerns," *2004-SID International Symposium Seminar Lecture Notes*, *Society for Information Display, Seminar* F-1, Vol. 2, pp. F-1/1-61 (2004).

P. Boynton, "The Challenge to Display Metrology and Standards: Whom Do You Trust?" *Workshop and Special Evening Session of the SID 24th International Display Research Conference*, pp. 46-57 (2004).

E. F. Kelley, "Plotting the Course of the Next VESA Flat Panel Display Measurements Standard," *2004-SID International Symposium Digest of Technical Papers, Society for Information Display*, Invited Paper 7.1, Vol. 35, Book 1, pp. 78-81 (2004).

E. F. Kelley and J. Penczek, "Scalability of OLED Fluorescence in Consideration of Sunlight-Readability Reflection Measurements," *2004-SID International Symposium Digest of Technical Papers, Society for Information Display*, Paper P.54, Vol. 35, Book 1, pp. 450-453 (2004).

P. Boynton, "Methods for Assessing Display Measurement Capabilities," *Cockpit Displays XI*, *Proceedings of the SPIE*, Vol. 5543 (2004).

P. A. Boynton, , E. F. Kelley, and J. M. Libert "Projection Display Metrology at NIST: Measurements and Diagnostics," *Liquid Crystal Materials, Devices, and Applications X and Projection Displays X, Proceedings of the SPIE*, Vol. 5289, pp. 302-313 (2004).

J. M. Libert, E. F. Kelley, P. A. Boynton, S. W. Brown, C. Wall, and C. Campbell, "A Color Gamut Assessment Standard: Construction, Characterization and InterLaboratory Measurement Comparison," *Fourth Oxford Conference on Spectroscopy*, *SPIE* Vol. 4826, pp. 146-164 (2003).

E. F. Kelley and A. Badano, "Characterization of Luminance Probe for Accurate Contrast Measurements in Medical Displays," *NISTIR 6974*, 15 pages (2003).

E. F. Kelley, "Sensitivity of Display Reflection Measurements to Apparatus Geometry," *2002 SID International Symposium Digest of Technical Papers, Society for Information Display*, Boston, MA, pp. 140-143 (2002).

E. F. Kelley, "Fundamentals of Display Metrology," 2002 *Society for Information Display International Symposium Short Course* S-3, *2002 SID International Symposium*, Boston, Massachusetts, 205 pp., May 19-24, 2002.

Interferometry and Polarimetry

Technical Contact:
Paul Williams

Staff-Years (FY 2004):
3.5 professionals
0.4 technician
1 student

Goals

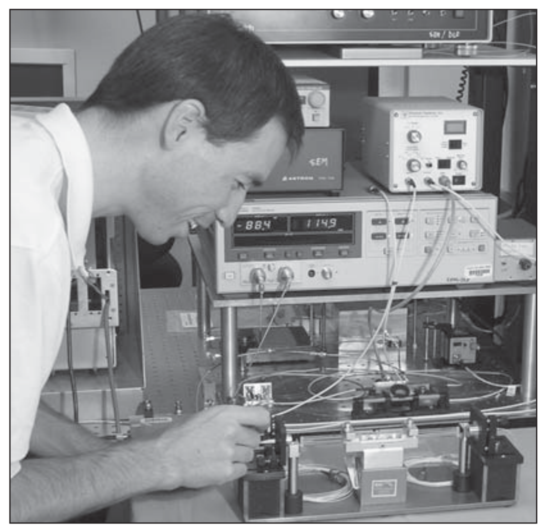
Provide supporting metrology for optical fiber applications ranging from telecommunications to sensing to medical imaging by providing measurements, calibrations, standards, and expertise, drawing on a strong technical background in interferometry and polarimetric techniques.

Customer Needs

Fiber Bragg Gratings (FBG) are widely used in both optical fiber sensors and optical fiber communications. As sensors, FBGs provide a reflectance spectrum whose center wavelength depends on the strain and temperature of the FBG. Accurate sensing requires characterization of the achievable stability and measurement accuracies for center wavelength. As wavelength splitters and filters used in telecommunications, FBGs require accurate spectral characterization of reflected intensity as well as group delay (particularly when FBGs are used in dispersion compensation). Also, direct measurements of the longitudinal index of refraction profile for FBGs are needed to assess the fidelity of the FBG inscription process, especially in the development of apodized and sampled gratings. Such metrology would also be useful to improve spatial resolution to sub-grating lengths for FBG sensors.

In the field of medical imaging, ***Optical Coherence Tomography (OCT)*** has demonstrated unprecedented spatial resolution of a broad range of measurement parameters. However, as a relatively young technology, OCT lacks sufficient metrology infrastructure. Fundamental to the benefit of OCT is its spatial resolution; resolutions as low as ~1 μm have been reported. However, accuracy verification is currently up to the instrument maker. Tissue characteristics such as refractive index and chromatic dispersion can affect both spatial accuracy and resolution. Characterized measurement techniques and artifacts (phantoms) of known spatial dimension are needed to enable uniform agreement of dimensional OCT measurements. For "functional OCT," index-of-refraction effects such as chromatic dispersion and birefringence also present the possibility of a sensitive means of tissue characterization. However, accurate and repeatable measurement techniques must be developed and characterized.

In optical-fiber communication systems, dispersion broadens the optical pulses, making it difficult to distinguish adjacent data bits, causing communication errors. Dispersion in optical fiber arises from the variation of the light's propagation velocity as a function of wavelength or polarization state. Mitigation of system ***chromatic dispersion*** (through dispersion-tailored fibers, choice of zero-dispersion wavelength, and dispersion-compensating fibers) requires accurate measurement of the wavelength dependence of chromatic dispersion, and the ability for users to verify this accuracy. Wavelength-dependent ***relative group delay (RGD)*** in optical components (such as narrow-band filters for 40 Gbit/s data rates) is more challenging as characterization requires sub-picosecond resolution in bandwidths on the order of tens of picometers. To simultaneously optimize these opposing resolutions requires improved measurement signal-to-noise ratio and drift reduction.



Aligning gas absorption cell used for fundamental calibration of chromatic dispersion and RGD measurements.

In ***polarization-mode dispersion (PMD)***, where propagation velocity depends on the polarization state of the light, communication systems can require PMD measurements to have temporal resolutions of tens of femtoseconds with spectral resolutions of tens of picometers. Again, this mutual resolution requirement requires low-noise measurements (high spectral efficiency). Additionally, at 40 Gbit/s data rates, characterization of ***second order polarization-mode-dispersion (SOPMD)*** is important.

Technical Strategy

We address the above metrology needs through the development of unique, high-resolution measurement techniques with rigorous uncertainty analysis, metrology transfer via calibrations, artifact development and distribution, measurement comparisons, and Special Tests of customer artifacts.

Optical Coherence Tomography (OCT): Our OCT efforts are currently focused on our core strengths of low-coherence interferometry, chromatic dispersion metrology, and polarimetry expertise. We will investigate the extent to which OCT measurements of chromatic dispersion can provide a sensitive means of tissue characterization and identification. Our work with fiber-optic components has given us extensive experience in the measurement of chromatic dispersion using low-coherence interferometry (the basis of OCT). We have demonstrated high-accuracy measurements of the spectral dependence of group delay of an absorbing gas, and have demonstrated good agreement between our measurements and theoretical predictions of the group delay. We have also analyzed the effects of measurement signal-to-noise ratio and the tradeoffs between group delay accuracy and wavelength resolution. Currently, chromatic dispersion is recognized as an impediment to the spatial resolution of OCT and is dealt with by providing compensating dispersion. We plan to go further and directly measure the chromatic dispersion as a function of wavelength in highly scattering media such as tissue or tissue-like phantoms. To validate the accuracy of such measurements, we will determine and demonstrate the achievable resolution for chromatic dispersion due to both instrument limitations and scattering effects. We will determine the accuracy to which the dispersion can be theoretically predicted from tissue constituents. These dispersion metrology efforts may be relevant to the determination of cell nucleus size, since the measured dispersion can be a function of the size of the scattering centers (nuclei). Accurate measurements of nucleus size may be an important early indicator of cancer. Additionally, dispersion measurements may have application in tissue identification, such as distinguishing between lipids, immune cells, and calcium in screening for diagnosis of heart disease.

We will also investigate the measurement of tissue birefringence using OCT. We will apply our 20+ years of polarimetry experience to enable accurate, low-noise measurements of tissue birefringence, which is often a useful measure of tissue condition. Many healthy tissues exhibit birefringence, and reduction of birefringence can indicate damage or disease such as burns or the onset of glaucoma.

PLAN: Continue development of high-accuracy OCT system. Determine accuracy limits of rapidly scanning delay-line OCT measurements, including the effects of nonlinear delay. If necessary, develop compensation techniques to correct the effects of nonlinear delay in a rapidly scanning optical delay line. Characterize background dispersion of rapidly scanning optical delay line. Develop measurements and theory to accurately determine the chromatic dispersion of a strongly scattering medium, such as tissue. Develop noise-reduction and averaging techniques to extract birefringence from materials exhibiting scattering and birefringence domains.

Optical Fiber Sensing of Bullet-Proof Vest Performance: We are investigating fiber optic sensing mechanisms for precise metrology of shape deformation and force distribution of bullet-proof vests.

PLAN: Determine appropriate sensing mechanism and evaluate its accuracy.

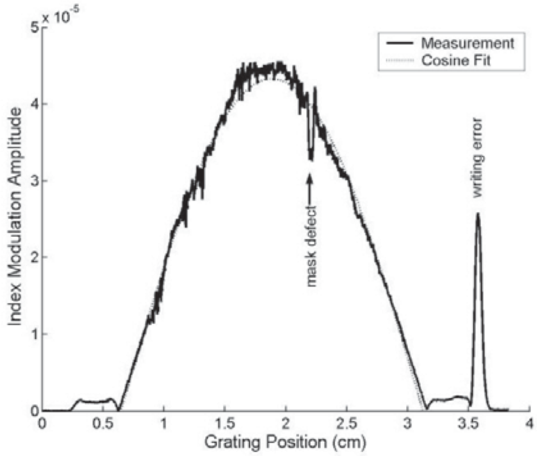
Chromatic Dispersion & Relative Group Delay: With our 2 GHz modulation phase shift (MPS) system we offer Special Test measurements of chromatic dispersion and zero-dispersion wavelength on customer-supplied fibers over the wavelength range from 1442 nm to 1620 nm. Using a 200 MHz MPS system, we are able to measure component group delay features with 0.072 ps resolution and a single spectral sweep accuracy of 0.46 ps with a spectral resolution of 3.2 pm. This capability is available to customers as a Special Test over the wavelength range of 1510 nm to 1620 nm.

PLAN: Our accuracies and resolutions of chromatic dispersion and RGD measurements are sufficient for near-term telecommunications needs; we have no plans for their expansion in the near future.

Polarization-Mode Dispersion (PMD): We offer PMD measurements on customer supplied artifacts, and provide artifact standards (Standard Reference Materials) for differential group delay (DGD). Our narrow-bandwidth PMD metrology yields DGD measurements with uncertainty of 9 fs in a 40 pm bandwidth. We have developed a prototype second-order PMD (SOPMD) artifact based on polarization-maintaining fiber.

PLAN: Our first-order PMD metrology is sufficient for the near-term. Improved SOPMD metrology development will be needed if 40 Gbit/s PMD compensation is implemented. We have suspended new PMD development pending indications that further SOPMD metrology is needed.

Optical Fiber Bragg Grating (FBG) Index Profile: We have the capability to measure FBG longitudinal index profile using a low-coherence interferometer to measure the grating's impulse response via the layer-peeling algorithm. This enables measurement of the FBG's longitudinal index profile with a spatial accuracy of ~100 µm. This technique allows in-situ assessment of grating writing fidelity as well as highly spatially resolved local-stress metrology on FBGs.



FBG index profile measured using low-coherence technique compared with a predicted cosine-fit.

PLAN: Work to increase measurement signal-to-noise ratio (SNR) and investigate improvements. Evaluate tradeoffs between grating length, grating strength, SNR, and accuracy.

Component Spectral Transmission/Reflection: We have the capability to characterize spectral reflection/transmission profile in fiber Bragg gratings with sub-picometer accuracy. This is supported by both frequency-domain and low-coherence interferometry approaches.

PLAN: Offer spectral reflectance profiling for component characterization.

Accomplishments

■ *FBG Longitudinal Index Profile Measurements.* We have successfully demonstrated the use of a low-coherence interferometer to measure the longitudinal index profile (apodization shape) of a 1.4-mm long FBG with a spatial accuracy of approximately 100 µm. The interferometric measurement was used to calibrate and identify errors in our scanning-beam/dithered-phase-mask FBG writing system.

■ *High-Accuracy Fiber Bragg Grating Sensor Calibrator.* We designed, built, and tested a high-accuracy calibration instrument for optical FBG strain and temperature sensors. This instrument provides four stabilized, calibrated FBGs at different wavelengths for use in calibrating strain sensor readout units. Expanded uncertainty of center wavelength is 2 pm. The FBG center wavelengths were determined using both a tunable laser system and low-coherence interferometry.

■ *Development of Metrology Infrastructure for Optical Coherence Tomography (OCT).* We have begun developing accurate OCT metrology based on our previous experience and infrastructure for low-coherence interferometry. We have demonstrated a high-scanning-speed reference mirror and are characterizing it for accuracy and inherent chromatic dispersion. We are also proceeding with investigations of chromatic dispersion and birefringence metrology for OCT.

■ *High-Spectral-Resolution PMD Measurement System Completed.* We have assembled, demonstrated and completely characterized the uncertainty for a 2.46 GHz Modulation Phase Shift (MPS) system for narrow-bandwidth measurements of differential group delay (DGD). The single-measurement uncertainty is 40 fs (~ 95 % confidence interval) in ~40 pm bandwidth. Averaging with reorientation of the fiber leads brings this value down to 9 fs. Uncertainty results depend on DGD.

■ *Modulator chirp and group delay interaction discovered and characterized.* For the modulation phase-shift technique of measuring relative group delay (RGD), we found modulator chirp causes an asymmetric error in the measured RGD spectrum for certain narrow features. We characterized the strength of this effect and demonstrated its mitigation. This effect presents the possibility of sensitive measurement of modulator chirp (α parameter resolution of 0.02).

■ *Participation in International Chromatic Dispersion Intercomparison.* We participated with four other national measurement institutes in a broad-spectrum international comparison of chromatic dispersion and zero-dispersion wavelength measurements. Preliminary results are published in the Technical Digest of the 2004 Symposium on Optical Fiber Measurements.

Collaborations

- University of Texas, OCT birefringence and chromatic dispersion metrology.

Standards Committee Participation

- IEC TC86/WG4 & IEC SC86C/WG3 Fiber Optics Calibration & Optical Amplifiers
- USTAG SC86A IEC U.S. Technical Advisory Group - Optical Fibers and Cables
- TIA FO-4 Committee on Fiber Optics, subcommittee Vice-Chair, working group Chair

Standard Reference Materials (See appendix E)

http://www.boulder.nist.gov/div815/SRMS/SRMS.htm

- SRM 2518/2538 Polarization-Mode Dispersion (Mode-Coupled / Non-Mode-Coupled).
- SRM 2513, Mode-Field Diameter of Single-Mode Fiber.
- SRM 2520, Optical Fiber Diameter

Measurement Services (NIST Special Tests)

- Optical Fiber Chromatic Dispersion and Zero-Dispersion Wavelength.
- Optical Linear Retardance Standard (nominal quarter-wave retarder)
- Polarization-Mode Dispersion, custom measurements

Recent Publications

http://www.boulder.nist.gov/div815/81503_pubs. htm

R. J. Espejo, S. D. Dyer, M. Svalgaard, "Analysis of a Fiber Bragg Grating Writing Process Using Low-Coherence Interferometry and Layer-Peeling," *Tech. Dig., Symp. on Optical Fiber Meas.*, Sept. 28-30, 2004, Boulder, Colorado, pp. 195-198 (2004).

S. D. Dyer, P. A. Williams, R. J. Espejo, J. D. Kofler, S. M. Etzel, "Key metrology considerations for fiber Bragg grating sensors," *SPIE 11th Annual Int'l Symp. on Smart Structures and Materials*, March 14-18, 2004, San Diego, California, pp. 181-189 (2004).

S. D. Dyer, R. J. Espejo, P. A. Williams, "High-resolution Group Delay Measurements of a Hydrogen Cyanide Gas Cell Using Low-coherence Interferometry," *Tech. Dig., Symp. on Optical Fiber Meas.*, Sept. 24-26, 2002, Boulder, Colorado, pp. 45-48 (2002).

T. Dennis and P. A. Williams, "Achieving High Absolute Accuracy for Group Delay Measurements Using the Modulation Phase Shift Technique," Submitted to *J. Lightwave Technol.*, 23 (2005).

T. Dennis and P. A. Williams, "Chromatic dispersion measurement error caused by source amplified spontaneous emission," *IEEE Photon. Technol. Lett.*, 16 pp. 2532-2534 (2004).

T. Dennis, P. A. Williams, "High-Accuracy Optical Group Delay Measurements and Modulator Chirp Characterization," *International Topical Meeting on Microwave Photonics*, Oct. 4-6, 2004, Ogunquit, Maine (2004).

P. A. Williams, J. D. Kofler, "Narrowband Differential Group Delay Measurement Using a 6-State RF Phase Shift Technique: 40 fs Single-Measurement Accuracy," *J. Lightwave Technol.*, 22 pp. 448-456, (2004).

W. C. Swann, S. D. Dyer, R. M. Craig, "Four-state Measurement Method for Polarization Dependent Wavelength Shift," *Tech. Dig., Symp. on Optical Fiber Meas.*, Sept. 23-25, 2002, Boulder, Colorado, pp. 125-128 (2002).

Spectral and Nonlinear Properties

Technical Contact:
Nathan Newbury

Staff-Years (FY 2004):
2.5 professionals
0.4 technician
1 post-doc

Goals

Develop techniques for the measurement of spectral and nonlinear properties of optical fiber and components and develop wavelength-calibration transfer standards in the near infrared region to help industry calibrate equipment. In collaboration with the NIST Time and Frequency Division, the project develops optical frequency combs for highly stable and accurate wavelength standards.

Customer Needs

In the past, this project concentrated on the measurement needs of the optical fiber communications industry. More recently our focus has expanded to address the broader needs for metrology and stable optical sources in the near-infrared region that arise in a variety of applications, including coherent communications, LIDAR, and optical fiber sensors.

By using many wavelength channels simultaneously, wavelength division multiplexing (WDM) has been very successfully applied to increasing the transmission bandwidth of optical-fiber communication systems. Most WDM systems employ 50 or 100 GHz channel spacing (0.4 or 0.8 nm, respectively) in the 1540 to 1560 nm region. For effective system operation, the source wavelength and the wavelength dependence of any components must be well characterized and controlled. In the past, this project has developed Standard Reference Materials (SRMs) that can provide wavelength standards in this region for calibration of measurement equipment. To support requirements of even higher bandwidths, future systems will either expand into other wavelength regions or increase transmission efficiency within the current spectral region. Expansion into other spectral regions will require broader wavelength-standard coverage across the near-infrared. Increased transmission efficiency may require even tighter control of the optical frequency, or, in other words, optical sources with higher frequency stability.

Partly because of the dramatic increase in the available sources and components at telecommunication wavelengths, this area of the spectrum finds increasing applications in sensing. For example, optical-fiber sensors can detect small changes in stress, or temperature, based on the wavelength shift of fiber Bragg grating reflection peaks. The sensitivity is determined by the wavelength accuracy of the interrogation unit; some systems need wavelength calibration to better than 1 pm. As another example, coherent LIDAR systems can be used to probe the atmosphere and for military sensing applications. Operation near 1.5 µm is attractive because it is eye-safe compared to the visible region, there is an abundance of available technology, and there are amplifiers available of increasingly higher power. The ability to generate and transmit highly frequency-stable (*i.e.*, low phase noise) optical sources translates directly into increased sensitivity for coherent LIDAR. Coherent free-space communications shares the same essential features as coherent LIDAR and will similarly benefit from well characterized, frequency-stable optical sources. Therefore, all of these applications share the same basic metrological needs of measuring an optical frequency. For wavelength calibration of an optical source, the measurement occurs on long time-scales and provides a value for the average absolute wavelength; for determination of the frequency stability, or the phase noise of an optical source, the measurement occurs on short time-scales and provides a value for the wavelength or frequency fluctuations.

Technical Strategy

Supporting optical fiber and component metrology needs requires development and evaluation of new measurement techniques, dissemination of this knowledge, and, when appropriate, development of Standard Reference Materials (SRM) or other calibration aids to help industry calibrate instrumentation. The project currently focuses on two areas: wavelength calibration standards in the near infrared region and nonlinear properties of optical fiber.

***Wavelength calibration standards*:** Fundamental wavelength references based on atomic and molecular absorption or emission lines provide the highest accuracy, but they are not available in all wavelength regions. The project currently produces four wavelength reference SRMs based on fundamental molecular absorption lines: SRM 2514 (carbon monoxide $^{12}C^{16}O$), SRM 2515 (carbon monoxide $^{13}C^{16}O$), SRM 2517a (acetylene, high resolution), and SRM 2519a (hydrogen cyanide). Together these SRMs can be used to calibrate the wavelength scale of instruments between 1510 nm and 1630 nm. WDM may expand into other wavelength regions, such as the 1300–1500 nm region. We have developed a hybrid multiple-wavelength reference in the 850-, 1300-, and 1550-nm regions that incorporates the wavelength flexibility of artifact references and the stability of fundamental molecular absorption references.

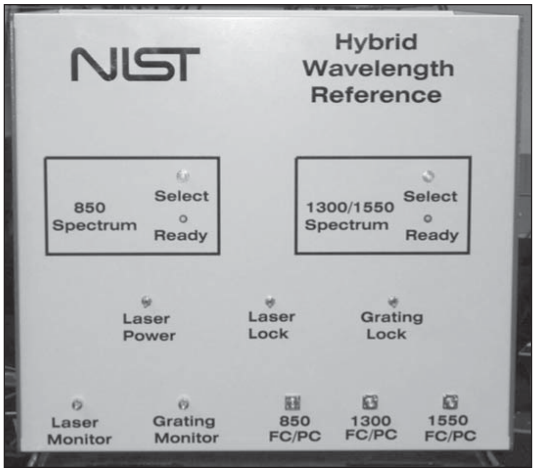


Figure 1. The hybrid wavelength calibration unit delivered to the Navy Primary Standards Laboratory.

NIST needs internal wavelength references of higher accuracy to calibrate its equipment. In collaboration with the NIST Time and Frequency Division, we have developed accurate frequency combs in the telecommunication wavelength region to measure other references. To generate an optical frequency comb in the near infrared, pulses from a mode-locked laser are launched into highly nonlinear optical fiber, which broadens the laser spectrum to a supercontinuum with a width of greater than 1000 nm. Since the laser is pulsed, this broad supercontinuum will actually be composed of discrete frequency lines – *a frequency comb* – spaced by the laser repetition rate. This optical frequency comb can be stabilized to provide discrete frequency or wavelength markers throughout the 1100–2000 nm region. Any unknown optical frequency can then be measured by simply comparing its frequency to that of the nearest tooth of the stabilized frequency comb. We have developed infrared frequency combs using both a mode-locked Cr:forsterite laser and several different mode-locked fiber lasers that can be self-referenced to a microwave source. The fiber laser-based systems can be much more compact, robust, power-efficient, and lighter than a bulk optic solid-state laser system. Ultimately, we envision that NIST-traceable optical frequency combs will meet internal and external wavelength calibration needs throughout the visible and near-infrared regions. One advantage of operating in the near IR is that the signals can be transmitted long distances over optical fiber. A single near-IR frequency comb could then be distributed over a fiber network to provide wavelength markers at different sites.

PLAN:

- Develop fiber frequency comb into tool for high accuracy (*i.e.*, subkilohertz) optical frequency measurement.
- Long term: Develop and implement plan to disseminate wavelength/frequency standards via optical frequency combs and optical fiber.

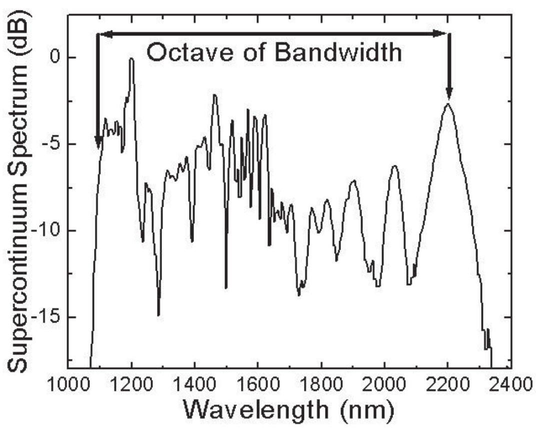


Figure 2. Supercontinuum output from fiber-laser based frequency comb.

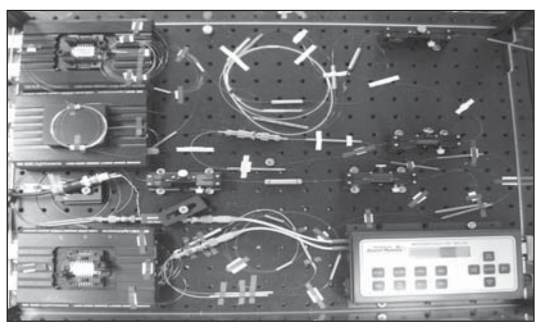


Figure 3. Photograph of the fiber-laser based frequency comb with a variable repetition rate

Nonlinear properties: Nonlinear effects in optical fibers can be extremely significant because the tight confinement of the light yields high intensities. A striking example of the nonlinear effects in optical fiber is provided by the generation of extremely broad spectra in optical fiber by launching femtosecond pulses into special nonlinear fiber. These broad spectra, or supercontinua, form the basis for the frequency combs discussed earlier. In addition, these supercontinua will find uses in optical coherence tomography and spectroscopy. For many applications, including frequency combs, the noise on the supercontinuum can be a limiting factor. Unfortunately, the same nonlinear processes that give rise to the supercontinuum also amplify any input noise. This can result in amplitude, phase and timing noise on the output. We have conducted extensive experimental and numerical studies of the noise on the visible supercontinua generated with Ti:sapphire modelocked laser pulses. We are currently exploring the noise on the infrared supercontinua generated with mode-locked fiber and Cr:Forsterite lasers.

Most applications exploiting the high frequency-stability of laser sources in the near infrared will require the transmission or distribution of the signal over optical fiber. For example, above we discussed distributing near-IR wavelength standards over a fiber network. However, the phase quality of either a narrow-linewidth laser or frequency comb launched in standard optical fiber will be degraded by both linear and nonlinear effects in the fiber. This fiber-induced phase noise can be the ultimate limit on the phase noise of a transmitted optical source. As a result, we are also interested in gaining a quantitative understanding of the nonlinear processes limiting transmission of narrow-linewidth sources down optical fiber. In a second, related area of nonlinear effects, we have developed a simple technique for determining the full wavelength dependence of the Raman gain.

PLAN:

- Investigate phase and amplitude noise on fiber-laser based supercontinuum sources
- Explore fiber-induced limitations to the dissemination of frequency combs and narrow laser lines over optical fiber networks.

ACCOMPLISHMENTS

■ ***High Accuracy Wavelength Calibration SRM 2519a for the 1530–1565 nm Region*** — The development of a new wavelength-calibration Standard Reference Material, SRM 2519a High Resolution Wavelength Calibration Reference for 1530–1565 nm is complete. The development involved highly accurate measurements of line centers, pressure shift, and pressure broadening of hydrogen cyanide absorption lines, detailed uncertainty analysis and documentation, and developing a prototype optical fiber coupled unit. The main difference between SRM 2519a and its predecessor, SRM 2519, is the use of a lower-pressure hydrogen cyanide cell to produce narrower lines and thus support higher resolution and applications of higher accuracy. The center wavelengths of 54 lines of hydrogen cyanide are certified with uncertainties ranging from 0.04 pm to 0.24 pm, an improvement by more than an order of magnitude over SRM 2519.

■ ***Hybrid Wavelength-Calibration Reference Delivered*** — The project completed the development, construction, evaluation, and documentation of a multiple-wavelength calibration reference. The wavelength calibration unit was delivered to the Navy Primary Standards Laboratory, San Diego, in April 2004 and will be used to calibrate their optical spectrum analyzer. The reference incorporates the wavelength flexibility of fiber Bragg grating artifact references and the stability of fundamental molecular absorption references. It uses interleaved sampled fiber Bragg gratings to produce multiple peaks in the 850, 1300 and 1550 nm regions, with one 1550 nm peak stabilized to a molecular absorption line. Twenty three peaks in the 850 nm region, 16 peaks in the 1300 nm region, and 22 peaks in the 1550 nm region are certified with 6 pm expanded uncertainty.

■ ***Raman Gain Measurements*** — We have developed and fully documented a simple technique to measure the full wavelength dependence of the Raman gain. We have also participated in a Telecommunications Industry Association round robin measurement.

■ ***Supercontinuum Noise Studies*** —Thorough studies of the amplitude and phase noise on optical supercontinuum pulses generated in microstructure optical fiber from pulses launched by a mode-locked Ti:Sapphire laser have been completed. During the supercontinuum formation, both the vacuum fluctuations and real amplitude noise on the input laser pulse can give rise to larger amplitude and phase noise across the supercontinuum. In 2002-2003, we undertook a systematic study of the amplitude noise across visible supercontinua generated using a Ti:sapphire laser. The project recently completed a complementary study of fundamental phase, timing, and frequency noise on the frequency comb. Fortunately, by carefully choosing the experimental conditions, the noise can be limited to low levels that do not interfere with the frequency metrology application.

■ ***Near-IR frequency measurements using Cr:Forsterite laser-based frequency comb*** — Project members, in collaboration with staff of the NIST Time and Frequency Division, have developed an infrared frequency comb to accurately measure optical frequencies across the near-infrared region from 1100 to 2000 nm, including the important telecommunication window from 1300 to 1600 nm. The system is based on a stabilized infrared-frequency comb, which comprises a mode-locked Cr:forsterite laser whose output is spectrally broadened in highly nonlinear fiber and then stabilized to both a hydrogen maser and the calcium optical frequency standard. To demonstrate the capability of the system and produce internal calibration standards, we measured three methane absorption lines in the 1300 nm region and a 1560 nm laser stabilized to a rubidium line.

■ ***Fiber laser-based frequency comb for frequency metrology in the infrared developed*** — Project members, in collaboration with OFS Technologies and a NIST Time and Frequency Division researcher have developed the first self-referenced phase-locked frequency comb in the near infrared. The phase-locked frequency comb is based on a mode-locked, erbium-doped fiber laser whose output is amplified and spectrally broadened in novel dispersion-flattened, highly nonlinear optical fiber to form a frequency comb spanning 1100–2200 nm in wavelength. This comb is stabilized to a microwave source by phase-locking both the repetition rate and the comb offset frequency using the now standard "f-to-2f" technique. At the end of 2004, we also have demonstrated a variable-repetition-rate frequency comb, which should have important metrological applications in both wavelength metrology and spectroscopy. For example, in wavelength metrology, the mode number of the relevant comb tooth that is heterodyned with the unknown laser can be determined without the need for an expensive high-quality wavelength meter.

Standard Reference Materials (SRM) (See appendix E)

http://www.boulder.nist.gov/div815/SRMS/SRMS.htm

SRM 2513, Mode Field Diameter Standard for Single-Mode Fiber

SRM 2514, Wavelength Calibration Reference for 1560–1595 nm – Carbon Monoxide $^{12}C^{16}O$

SRM 2515, Wavelength Calibration Reference for 1595–1630 nm – Carbon Monoxide $^{13}C^{16}O$

SRM 2517a, High Resolution Wavelength Calibration Reference for 1510–1540 nm – Acetylene $^{12}C_2H_2$

SRM 2519a, High Resolution Wavelength Calibration Reference for 1530–1565 nm – Hydrogen Cyanide $H^{13}C^{14}N$

SRM 2520, Optical Fiber Diameter Standard

Recent Publications

http://www.boulder.nist.gov/div815/81503_pubs.htm

B. Washburn, S. A. Diddams, N. R. Newbury, J. Nicholson, F. Kenneth, P. S. Westbrook, C. G. Jorgensen, "A tunable repetition rate, fiber laser-based frequency comb for infrared frequency metrology," in *Tech. Digest, Symposium on Optical Fiber Measurements (SOFM 2004)*, NIST Special Publication 1024, pp. 11-14 (2004).

B. R. Washburn and N. R. Newbury, "Phase Timing and Amplitude Noise on Supercontinua Generated in Microstructure Fiber," *Optics Express*, Vol. 12, No. 10, pp. 2166-2175 (2004).

M. A. Rowe, W. C. Swann and S. L. Gilbert, "Multiple Wavelength Reference Based on Interleaved, Sampled Fiber Gratings and Molecular Absorption," *Appl. Opt.*, Vol. 43, No. 17, pp. 3530-3534 (2004).

K. L. Corwin et al, "Absolute Frequency Measurements with a Stabilized Near-Infrared Optical Frequency Comb from a Cr:Forsterite Laser," *Opt. Lett.*, Vol. 29, No. 4, pp. 397-399 (2004).

B. Washburn, J. Nicholson, C. G. Jorgensen, M. F. Yan, S. A. Diddams and N. R. Newbury, "Phase-Locked, Erbium-Fiber-Laser-Based Frequency Comb in the Near Infrared," *Opt. Lett.*, Vol. 29, No. 3, pp. 250-252 (2004).

T. J. Drapela, S. L. Gilbert, W. C. Swann, and C.–M. Wang, "The NIST Traceable Reference Material Program for Wavelength Reference Absorption Cells," *NIST Special Publication 260-151* (2003).

K. L. Corwin, N. R. Newbury, J. M. Dudley, C. Coen, S. A. Diddams, B. Washburn, K. Weber and R. S. Windeler, "Fundamental Amplitude Noise Limitations to Supercontinuum Spectra Generated in a Microstructured Fiber," *Appl. Phys.* B. Vol. 77, pp. 269-277 (2003).

N. R. Newbury, "Pump Wavelength Dependence of Raman Gain in Single-Mode Optical Fibers," *J. Lightwave Technol.*, Vol. 21, No. 12, pp. 3361-3373 (2003).

N. R. Newbury, B. Washburn, K. L. Corwin and R. S. Windeler, "Noise Amplification During Supercontinuum Generation in Microstructure Fiber," *Opt. Lett.*, Vol. 28, No. 11, pp. 944-946 (2003).

K. L. Corwin, N. R. Newbury, J. M. Dudley, S. Coen, S. A. Diddams, K. Weber and R. S. Windeler, "Fundamental Noise Limitations to Supercontinuum Generation in Microstructure Fiber," *Phys Rev. Lett.*, Vol. 90, pp. 113904-1 to 113904-4 (2003).

Optical Materials Metrology

Technical Contact:
Norman Sanford

Staff-Years (2004):
2 professionals
2 post-doctoral researchers

Goals

Develop complementary metrology methods of nonlinear optical analysis, near-field optical spectroscopy, confocal microscopy, time-resolved photoluminescence, and X-ray diffraction analysis for studies of optical, electronic, and structural properties of bulk and thin-film III nitrides, quantum nanowires, and nitride device structures. Accumulate a database of refractive index and birefringence for AlGaN and InGaN alloy semiconductors. Develop prototype ultrafast and ultrastable, narrow-line, cw solid-state waveguide lasers.

Customer Needs

Customer needs fall into three main categories: (1) metrology suites for rapid non-destructive characterization of photonic materials in terms of optical, electronic, and structural characteristics for bulk crystals and thin films; (2) semiconductor nanowire technology and metrology for sensing, biomedical, materials science and electronics applications; (3) specialized ultrafast and continuous-wave solid-state waveguide lasers for applications in analog-to-digital conversion, secure communications, and RF synthesis.

GaN and related materials have made enormous recent economic impact with the realization of semiconductor lasers and LEDs emitting in the blue and UV for display, optical data storage, water purification, and biological agent detection. Other important applications of this material system include high-power, high-temperature transistors and solar-blind UV detectors. Problems with bulk and thin-film growth of these materials remain, however, hindering the ability to meet the application demands. There persists a fundamental lack of understanding of the role of defects on the electrical, optical, and structural properties of these materials. These issues compel the development of new correlated metrology methods, with resolution on the scale of 20 to 100 nm. Furthermore, the lack of a database for the linear optical properties of the III nitrides is hampering development of engineering design tools for blue-emitting GaN-based laser diodes.

Semiconductor quantum nanowires (SQNWs) offer new revolutionary applications in biological/chemical sensors, *in-vivo* biomedical diagnostics and therapies, nanoscale electronics, optoelectronics, and nanoscale thermal management. For example, SQNW lasers with emission apertures roughly 20–100 nm in diameter (about the size of a virus) would permit development of a new class of tools for ultra-high-resolution microscopy and cellular-level imaging. In pursuing such new capabilities, researchers and technologists must confront the fact that fundamental physical properties do not often scale from macro to nano regimes, and that many relevant nanoscale metrology practices are immature or nonexistent. For SQNWs, these issues force an unusually strong coupling of technology development with metrology, and create new challenges and opportunities for both.

Compact, solid-state waveguide lasers and amplifiers are emerging as a technology with impact ranging from telecommunication to high-speed signal processing to high-speed detector metrology. With assistance from industrial collaborators, NIST has been on the cutting edge of developing technology for these application areas. Customer needs range from the optical characterization of laser glasses, to the testing of the impact of fabrication methods on laser performance, to the development of specialty lasers for all-optical, analog-to-digital conversion or coherent communication applications. The lasers may also find use in long-distance distribution of optical atomic-clock signals over fiber.

Technical Strategy

Photoluminescence spectroscopy of group III-nitrides – Multi-photon luminescence (MPL) spectroscopy offers a means by which the uniformity of an active (buried) quantum well layer in a III-nitride laser or LED structure can be probed regardless of the thickness of the surrounding layers. Standard direct above-bandgap photoluminescence (PL) spectroscopy is problematic since the pump beam could be absorbed elsewhere in the structure before exciting the regions of interest. Using MPL spectroscopy, even embedded structures may be examined. Furthermore, it has been demonstrated that MPL intensity in GaN that scales with a non-integer exponent of pump intensity is suggestive of the presence of saturable midgap defect states. We will correlate MPL measurements with CL results, obtained when the capping layer is thin enough (~20 nm) to allow CL examination of the active region through the capping layer, and with those of more realistic device structure where the active layer is buried hundreds of nanometers within the structure. We will continue the development of collection-mode near-field optical methods and examine the group III-nitrides using SHG and photoluminescence (PL) spectroscopies on a resolution scale of 20–100 nm.

PLAN: Correlate near-field optical measurements and MPL studies with CL studies and other high-resolution electron-beam and X-ray metrologies, working closely with collaborators in the NIST Materials Science and Engineering Laboratory (MSEL) and Chemical Science and Technology Laboratory (CSTL). We will apply nanoscale spatially and temporally resolved spectroscopy to the study of AlGaN and InGaN material, thin film structures, and nanowires fabricated in wide-bandgap semiconductors.

Electrically addressable optoelectronic nanowires – We will fabricate UV-blue lasers from SQNWs. The SQNWs will be grown in the group III-nitride semiconductor system by plasma-assisted MBE. Required attributes include high purity, low defect density, the ability to engineer heterostructures and make electrical contact, and precise doping control. A suite of test structures will be developed which will include intrinsic, p- and n-doped wires, "core-sleeve," and axially alternating junction/heterostructures of SQNWs. We will develop new techniques involving block-copolymer template photolithography and electron-beam lithography and apply these methods to the patterned growth of SQNWs. We will develop new techniques to form electrical contact individually or to arrays of SQNWs. We will use AFM, XRD, TEM, FESEM, Raman spectroscopy, and electron-backscattering diffraction (EBSD) for the structural characterization in this work.

PLAN: Demonstrate optically pumped group III-nitride nanowire lasers. After further development, we will demonstrate electrically addressable nanowire lasers.

Refractive index measurements of group III-nitrides – We have compiled refractive-index and birefringence data for a number of AlGaN samples ranging in composition from pure GaN to pure AlN, using prism coupling to waveguide mode techniques that are correlated with spectroscopic reflection and transmission measurements (performed by collaborators in MSEL). We also have measured refractive index of InGaN for low In mole fractions of technological interest. The wavelength span of the measurements is currently from 442 nm to 1064 nm. Extension of the measurements into the ultraviolet region requires developing waveguide grating coupling techniques correlated with spectroscopic reflection and transmission work. Also, calibration of composition of epilayers using techniques such as energy-dispersive x-ray spectroscopy (EDS) and Rutherford backscattering spectroscopy (RBS) is critical. Finally, correlation of x-ray diffraction studies with this suite of measurements is important in order to correlate the "bowing" of lattice constants with alloy composition. X-ray diffraction (XRD) is also used to establish film thicknesses in order to facilitate prism-coupled refractive index measurements of multilayer III-nitride alloy structures.

PLAN: Perform a comparison of XRD-derived layer thickness for GaN/InGaN test samples with layer thicknesses derived from cross-sectional field-emission scanning electron microscopy (FESEM) studies to potentially reduce the uncertainty in measurements of refractive index.

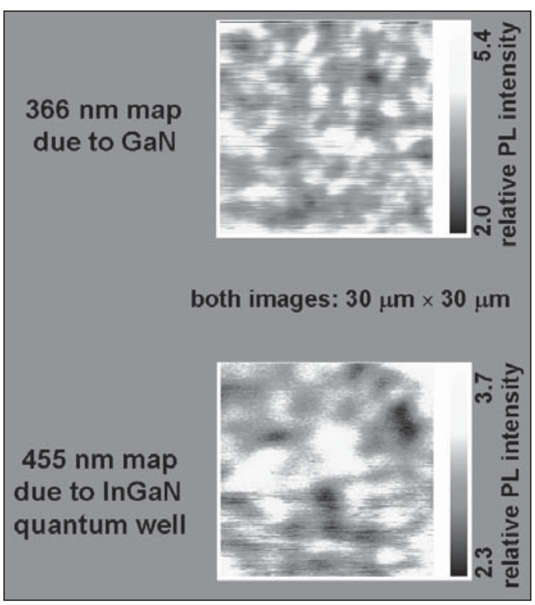
Solid-state waveguide lasers – We are developing cw and mode-locked solid-state waveguide lasers using ion-exchange in rare-earth-doped phosphate glasses. The optical, thermal, and chemical properties of the glass are measured and optimized in collaboration with a major U.S. glass manufacturer. Unlike semiconductor laser sources, the solid-state sources benefit from a long upper-state, laser-transition lifetime (~10 ms) that allows low-noise production of mode-locked pulses independent of repetition rate and low-noise generation of narrow-linewidth light. Unlike fiber laser sources, waveguide laser sources have sufficient rare-earth doping concentrations (~10^{20} cm^{-3}) to provide gain and power for short (~2 cm) device lengths. This permits high repetition rates without the complications associated with harmonic-mode locking (common in fiber lasers). We have demonstrated cw mode-locked operation using a semiconductor saturable absorber mirror. We will lock the output of the mode-locked laser to an optical frequency standard to assess short and long term stability and drift. Narrow-linewidth lasers have been fabricated using a distributed Bragg reflector (DBR) etched directly onto the waveguide structure.

PLAN: Pursue the application of waveguide lasers to coherent communication applications in collaboration with NIST and industry collaborators.

Accomplishments

■ **Confocal and NSOM multi-photon luminescence studies of InGaN** – Room-temperature confocal MPL studies were performed with an ultrafast Ti:sapphire laser (λ_c ~ 800 nm, 20 fs, peak intensity ~15 TW/cm^2) on a number of MOCVD-grown samples. They consisted of a sapphire substrate, nucleation layer, GaN sublayer, InGaN quantum well (QW) or thicker (300–400 nm) layer, and GaN cap.

In the QW sample, the GaN MPL (emission at 366 nm) demonstrated a pump-power exponent (PPE, exponential scaling of the MPL emission intensity with pump intensity) of 3.1 while the MPL from the QW (emission at 450 nm) yielded a PPE=2.9. For the thick InGaN sample with an In mole fraction of 6 % we observed a PPE of about 3.5. In the MPL of a bulk free-standing HVPE grown GaN sample (emission at 360 nm) we observed a PPE=3.0. Collection-mode near-field scanning optical microscopy (NSOM) was used to map the MPL from the QW sample. Ultrafast excitation through the polished back surface of the substrate produced MPL from both the QW and the adjacent GaN. The spatial resolution of the NSOM tip was estimated to be 300 nm. For the pump wavelength used in these experiments we expected to see PPE=3.0 for emission from GaN (~360 nm). The observation of non-integer PPE values for the InGaN layers (expect PPE=2 for QW and PPE=3 for thick layers) suggests the mediating role of defects, impurities, and/or phase separation in the multiphoton excitation process. Room-temperature NSOM mapping on a 30 x 30 mm region revealed large (greater than 50 %), uncorrelated intensity fluctuations (length scale less than 1 µm) in the respective MPL maps of the QW and the neighboring GaN layer. Ongoing imaging work will provide more insight into the role of localized defects and inhomogeneities in nonlinear spectroscopic studies of these materials.



Ultrafast multiphoton NSOM PL mapping of the uniformity of GaN and buried InGaN quantum well.

■ **Optical and structural characterization of wide-bandgap nanocolumns –** We performed room-temperature and low-temperature photoluminescence measurements, x-ray diffraction, FESEM, cathodoluminescence, and transmission electron microscopy measurements, in collaboration with other NIST groups, on GaN nanocolumns grown at NIST and by Air Force Research Laboratory (AFRL) collaborators. The x-ray studies indicated structural coherence of the nanocolumns and the strain relaxation in the nanocolumns relative to consolidated films of comparable thickness. The PL spectrum was broadband with peaks indicating the presence of excitons bound to as-yet unidentified structural defects.

■ **Refractive index of InGaN measured** – We measured the refractive index and birefringence of $In_xGa_{1-x}N$ films grown on GaN layers using prism coupling in conjunction with multilayer optical waveguide analysis. Samples of engineering interest supplied by Lumileds, with x ranging from 0.036 to 0.066, were examined at the separate wavelengths of 442, 457.9, 476.5, 488, 514.5, 532, and 632.8 nm. The In fraction x was determined by Rutherford backscattering spectroscopy by collaborators at Rutgers University. Separate measurements of the film thicknesses were performed by cross-sectional field-emission scanning electron microscopy (FESEM) by researchers in NIST MSEL. It was determined that the ordinary index n_o is a weak function of both x and wavelength for the InGaN layers and could be well distinguished from GaN (x = 0) only for the two shortest wavelengths used. On the other hand, the extraordinary index n_e for the InGaN layers was resolved from GaN for all the wavelengths and x values. The results for n_o corroborate similar measurements reported in the literature, of which there are very few reports for $In_xGa_{1-x}N$. They complement our published results on the measurement of AlGaN refractive index. More precise measurements of layer thicknesses by use of x-ray diffractometry and cross sectional TEM are in process to reduce the computed uncertainty (± 0.01) for the InGaN refractive indices.

■ **Low-jitter waveguide laser** – We demonstrated record-low-jitter pulse trains in a passively mode-locked, glass waveguide laser using high-bandwidth feedback control acting on the physical cavity length and optical pump power. In collaboration with JILA scientists, synchronization of the laser to an external clock signal yielded a root-mean-square relative timing jitter of 14.4 fs integrated from 10 Hz to the Nyquist frequency of

375 MHz. The jitter was lower than the lowest reported timing jitter of a mode-locked laser diode (20 fs from 1 Hz to 10 MHz), which is expected to have a higher contribution to jitter beyond 10 MHz than the glass waveguide laser. This work was funded by DARPA.

Collaborations

JILA – studies and methods of stabilization for solid-state lasers

NIST Materials Science and Engineering Laboratory – TEM, EBSD, CL, and XRD studies of III-nitride films and nanostructures, and studies of electrical contacts to these materials

NIST Chemical Science and Technology Laboratory – XRD and PL analysis of ZnO nanowires and Raman studies of III-nitride films

Lumileds – studies of refractive index of AlGaN and InGaN layered structures, and MPL studies of such structures

Schott Glass Technologies – glass development for solid state waveguide lasers

Recent Publications

N. A. Sanford, L. H. Robins, M. H. Gray, Y. –S. Kang, J. E. Van Nostrand, C. Stutz, R. Cortez, A. V. Davydov, A. Shapiro, I. Levin, A. Roshko, "Fabrication and analysis of GaN nanorods grown by MBE," submitted to *Physica Status Solidi (C)* 2004.

N. A. Sanford, A. Munkholm, M. R. Krames, A. Shapiro, I. Levin, A. V. Davydov, S. Sayan, L. S. Wielunski, T. E. Madey, "Refractive index and birefringence of InGaN films grown by MOCVD," submitted to *Physica Status Solidi (C)* 2004.

N. A. Sanford, A. Davydov, D. V. Tsvetkov, V. A. Dmitriev, S. Keller, U. Mishra, S. P. DenBaars, S. S. Park, J. H. Han, "Measurement of Second Order Susceptibilities of GaN and AlGaN," submitted to *J. Appl. Phys*. 2004.

B. Callicoatt, J. B. Schlager, R. K. Hickernell, R. Mirin, N. A. Sanford, "Compact Solid-State Waveguide Lasers," *IEEE Circuits and Devices*, Vol. 19, No. 5, pp. 18-27 (01-Sep-2003).

J. B. Schlager, B. Callicoatt, R. Mirin, N. A. Sanford, D. J. Jones, J. Ye, "Passively Mode-locked Glass Waveguide Laser with 14 fs Timing Jitter," *Opt. Lett*., Vol. 28, No. 23, pp. 2411-2413 (01-Dec-2003).

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K. W. Holman, D. J. Jones, S. T. Cundiff, J. Ye, J. B. Schlager, E. P. Ippen, "Optical Phase-coherent Link Between an Optical Atomic Clock and 1550-nm Mode-locked Lasers," *Tech. Dig., Conf. on Lasers and Electro-Optics (CLEO)*, Jun 01-06, 2003, Baltimore, Maryland, 2 pp. (01-Jun-2003).

J. S. Hayden, R. D. Simpson, S. D. Conzone, R. K. Hickernell, B. Callicoatt, A. Roshko, N. A. Sanford, "Passive and Active Characterization of Hybrid Glass Substrates for Telecommunication Applications," *Proc. Intl. Soc. for Optical Engineering (SPIE), SPIE*, Jan 23-24, 2002, San Jose, California, Vol. 4645, pp. 43-50 (01-Jan-2002).

Nanostructure Fabrication and Metrology

Technical contact:
Richard Mirin

Staff:
3 professionals
3 post-doctoral researchers
1 graduate student

Goals

Develop modeling, fabrication, and measurement methods for semiconductor nanostructures, including quantum dots and photonic crystals. Develop fundamentally new devices such as single-photon sources and detectors and entangled-photon sources.

Customer Needs

Semiconductor nanostructures, especially self-assembled quantum dots and photonic crystals, are emerging as an important future direction for optoelectronics. Photonic crystals offer a wide range of possibilities, ranging from improved light-emitting diodes to photonic integrated circuits to spontaneous emission control. Semiconductor quantum dots have an atomic-like density of states that offers substantial opportunities for unique and improved devices. These include ultra-low-threshold laser diodes with low temperature dependence and semiconductor optical amplifiers with reduced cross-gain modulation and large bandwidth. Several fundamental properties of quantum dots have yet to be measured, including resonant absorption cross-sections and homogeneous linewidth. These set limitations on device operation. For example, little detailed knowledge of the transition dipole moment of QDs has been available to date, although it is critical in determining gain for QD laser design and in implementing the coherent manipulation of the QD state in quantum logic gates that may be part of future-generation optical computers.

The ability to generate and control single photons offers new opportunities to meet customer needs in quantum-based radiometric measurements where optical power is measured by counting photons. Quantum cryptography is an emerging form of ultrasecure communications that requires an on-demand source of single photons. The single-photon turnstile will allow us to meet the requirements of this new technology. It can be extended to generate pairs of entangled photons. These entangled-photon pairs are useful for a wide range of applications, from fundamental tests of quantum mechanics to reduced dimensions with optical lithography.

Technical Strategy

Growth and characterization of semiconductor quantum dots – We use molecular beam epitaxy (MBE) to grow self-assembled quantum dots. Photon counting and cavity-ringdown methods are required to measure the optical properties of semiconductor nanostructures, particularly single quantum dots or small ensembles of dots. We have developed ultrafast pump-probe methods to characterize carrier lifetimes of quantum dots. We have used a novel time-resolved waveguide-coupling method to directly measure the dipole moment of quantum dots. Cavity ring-down spectroscopy provides an extremely sensitive direct measurement of absorption. Differential transmission spectroscopy yields information on carrier transfer and an estimate of the homogeneous linewidth of quantum dots. Spectral hole burning techniques will be used to directly measure the linewidth.

PLAN: We will directly measure the homogeneous linewidth of semiconductor quantum dots.

Single photon sources – For practical implementation, single-photon sources should operate at high temperatures. Colloidal CdSe quantum dots, nitrogen vacancy centers, and single molecules have demonstrated room-temperature single-photon emission; however, the first two systems exhibit blinking, and some single molecules exhibit photobleaching, both of which degrade performance. Epitaxial InGaAs/GaAs quantum dots are attractive as single photon emitters due to their ease of fabrication and inclusion with monolithic microcavities, their short spontaneous emission lifetimes, and the possibility of electrical injection.

The photon repetition rate of the single-quantum-dot, single-photon turnstile (SPT) is controlled by the frequency of an applied AC voltage, allowing precisely defined emission of single photons. The ultimate goal is the embedding of a SPT inside a photonic crystal nanocavity, which will enable enhanced emission efficiency and directionality. We have implemented a Hanbury Brown-Twiss apparatus to measure the photon statistics from our SPT. A true single-photon device exhibits photon emission times that are nonclassical. Specifically, photon antibunching has been observed.

PLAN: Demonstrate an electrically driven single photon turnstile based on a single quantum dot.

Single-photon detectors – Photon detectors made with field-effect transistors (FETs) that use an optically addressable floating gate consisting of a layer of quantum dots have the potential to be fast, flexible, and efficient single-photon detectors. With quantum dots one can control the absorption spectrum via material choices. In addition, resonant-cavity designs, which raise the efficiency, are compatible with these structures.

PLAN: Demonstrate a single-photon detector consisting of an optically modulated, quantum-dot field-effect transistor. The detector will be compact, and of low noise, and have a high quantum efficiency (goal of greater than 90 %).

Semiconductor photonic crystals – Photonic crystal cavities and waveguides are expected to play important roles in advanced optoelectronic devices such as ultracompact photonic integrated circuits for communication and sensing. The fabrication of photonic crystals requires the precision growth and anisotropic etching of semiconductor epilayers. We are using a chemically assisted ion-beam (CAIBE) system to etch semiconductor nanocavities in layers grown by MBE. These nanocavities contain quantum dots, and the spontaneous emission from the quantum dots is influenced by the effects of the cavity. Careful control of the cavity structure and the position of the quantum dots within the cavity can lead to weak coupling (enhanced spontaneous emission, also known as the Purcell effect) or to strong coupling (Rabi oscillations).

PLAN: Incorporate quantum dots in a photonic crystal cavity and characterize the coupling. Investigate the application of photonic crystals to single photon sources and other devices and develop pertinent measurement tools and techniques for the study of photonic crystal devices.

Mode-locked quantum dot lasers – There are many applications of ultrashort/broadband optical pulses that are hindered by the cost, complexity and inefficiency of the large-frame mode-locked lasers used to produce such pulses. These include optical atomic clocks, terahertz generation for homeland security, and optical coherence tomography (OCT). The problems would be eliminated if high-performance mode-locked diode lasers could be developed. Efforts to develop mode-locked diode lasers ran up against a fundamental barrier that limited the brevity of the pulses – carrier dynamics in the gain region of semiconductor lasers that result in a complex phase profile of the generated pulse. Ultimately 200 fs pulses have proven to be the shortest achievable from a conventional mode-locked diode laser, *i.e.*, one that uses a simple heterojunction or quantum well(s) for the gain region. This falls well short of the performance (~20 fs pulses) required for the most promising applications.

We plan to overcome this fundamental barrier by utilizing self-organized quantum dots for the gain region. It is anticipated that the quantum dots will be immune to the deleterious effects of complex carrier dynamics and enable a major improvement of pulse durations. In addition, the inherent size distribution in self-assembled QD ensembles leads to a very large inhomogeneously broadened lineshape with the bandwidth necessary to support short-pulse mode locking. This project requires a close coupling between expertise in QD growth, semiconductor laser design and fabrication, and in ultrafast lasers and measurement.

PLAN: Develop mode-locked quantum-dot diode lasers, with an ultimate goal of 20 fs pulse width, and characterize their output.

Accomplishments

■ **Dipole Moment of Semiconductor Quantum Dots Measured –** We developed a new technique to directly measure the dipole moment of QDs and applied it to self-assembled InGaAs/GaAs dots. It relies on the measurement of pulses of light that exit an optical waveguide containing the QDs as the light reflects multiple times from the waveguide facets. Light that is coupled out of the waveguide is mixed with a variably delayed gating pulse in a nonlinear crystal to time-resolve the output. The absorption coefficient is determined by comparing the energy of successive pulses and taking into account the measured waveguide facet reflectivity and background absorption, as determined from measurements of a waveguide that does not contain QDs. The dipole moment is derived from the ground-state absorption and the QD areal density, which was determined from transmission electron micrographs generated by collaborators at the National Renewable Energy Laboratory. The dipole-moment measurement technique overcomes the large uncertainties in previous measurements by other researchers that were based on threshold currents of laser diodes or that had large background material absorption or difficulty estimating coupling efficiency into and out of the QD region.

■ **Carrier dynamics of quantum dots measured** – We have investigated the process of carrier transfer between self-assembled InGaAs/GaAs quantum dots (QDs) near room temperature. By employing two-color differential transmission (DT) measurements we determined conclusively, for the first time, that carrier transfer occurs between QDs resonant with pump excitation and those initially empty. In addition, the width of the initial spectral hole produced an estimate for the homogeneous broadening in the QDs. The temperature dependence of the escape rate was also measured using degenerate DT spectroscopy, indicating that carriers initially escape to the wetting layer before being recaptured by other dots.

■ **Cavity ring-down spectroscopy of quantum dots –** We have developed cavity ring-down spectroscopy as a method for making high-precision measurements of fundamental properties of quantum dots (QDs). The ring-down cavity for the measurements was composed of an AlAs/GaAs distributed Bragg reflector on top of which InGaAs quantum dots were integrated, and a curved conventional, dielectric-coated, low-loss mirror attached to a piezo-electric transducer (PZT). The spectral profile of the quantum dots absorption was determined by measuring the decay dynamics of the intracavity field as a function of the wavelength of the probe laser, which was a cw frequency-stabilized Ti:sapphire laser. To relate the ring-down measurement to the QD absorption, we examined the photoluminescence signal of the quantum dots to obtain a qualitative measurement of the variations in QD density, carefully characterizing the dielectric mirror and performing low-precision photospectrometer measurements of the DBR mirror reflectivity to determine its stop band. By incorporating a QD density variation into the QD/DBR structure, the cavity loss as a function of wafer position allowed the loss contribution due to the QD absorption to be observed.

■ **Single-Photon Source at High Temperature** – We have demonstrated photon antibunching from a single, self-assembled InGaAs quantum dot at temperatures from 5 K up to 135 K, and single-photon emission on demand up to 120 K. The results represent the highest reported temperature for non-classical light emission from the InGaAs/GaAs system. InGaAs quantum dots were grown using molecular beam epitaxy and single dots isolated with etched mesas. The second-order intensity correlation, which is a measure of the independence of single-photon emitters, was derived by measuring the coincidence photon counts in a Hanbury Brown-Twiss interferometer, and it verified the antibunching. Contributions to the emission other than that from the uncharged single exciton were separated by analysis of the photoluminescence spectra. Single injection of electron-hole pairs by electrical means should improve the performance of an InGaAs quantum-dot single-photon source by removing the possibility of formation of charged excitons or biexcitons.

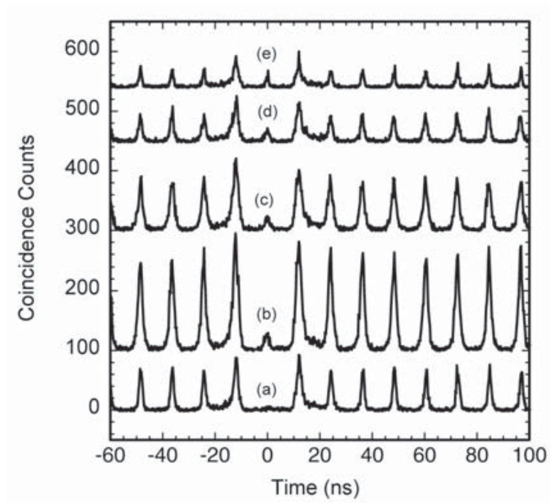

Figure 1. Second-order intensity correlation of single-photon source measured as a function of temperature. (a) 5 K, (b) 50 K, (c) 100 K, (d) 120 K, and (e) 135 K.

■ **Quantum-dot gated field-effect transistor for single photon detection** – We demonstrated an optically modulated field-effect transistor. Our devices are made with a GaAs/AlGaAs modulation-doped heterostructure. The two-dimensional electron gas (2DEG) formed at the GaAs interface is shaped into a long narrow channel. The conductance of this 2DEG channel is modulated by the charge stored in a layer of InAs quantum dots above the channel. Absorbed photons generate electron-hole pairs in the high-field region of the device. The field separates the charges, and the photogenerated holes are captured by the quantum dots, whereas the electrons are captured by the 2DEG and increase the conductivity. Our initial results with the FET were at a temperature of 5 K. Illumination with 904 nm photons caused the channel's conductance to rapidly increase. The lowest illumination we demonstrated is only 20 fW (90,000 photons/s), and even this power saturates the detector. We expect that by further reducing the optical power we will get to the point where the devices are sensitive to single photons.

■ **Photonic crystal laser** – We have demonstrated advances in fabrication and design of photonic crystals. A new masking technique that enables deep vertical etching of GaAs-based structures has been developed. We demonstrated vertical-cavity surface-emitting laser with lateral confinement provided by a photonic crystal cavity has been demonstrated. Two dimensional photonic crystal cavities with mode volumes approaching the theoretical limit have been fabricated. A comparison of the quality factors of three different types of cavities (micropillar, micropillar with lateral photonic crystal, and two dimensional photonic crystal) is in progress.

Key Collaborations:

JILA – Cavity ring-down spectroscopy and dipole measurements of quantum dots and other various projects.

Yale Univ. – Investigation of radiation pressure on cantilevers.

Recent Publications

R. Mirin, "Photon Antibunching at High Temperature from a Single InGaAs/GaAs Quantum Dot," *Appl. Phys. Lett.*, Vol. 84, No. 8, pp. 1260-1262 (23-Feb-2004).

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K. Ullmann, M. Su, K. L. Silverman, J. J. Berry, T. E. Harvey, R. Mirin, "Photoluminescence from an Nd3+ doped AlGaAs semiconductor structure," *Tech. Dig., Conf. on Lasers and Electro-Optics (CLEO)*, May 16-21, 2004, San Francisco, California.

J. J. Berry, T. E. Harvey, R. Mirin, J. Ye, "Cavity ring-down spectroscopy of semiconductor quantum dots," *Tech. Dig., Conf. on Lasers and Electro-Optics (CLEO), Annual Conference on Lasers and Electro-Optics (CLEO) and the Quantum Electronics and Laser Science Conference (QELS)*, May 16-21, 2004, San Francisco, California.

K. L. Silverman, R. Mirin, S. T. Cundiff, "Carrier transfer between InGaAs/GaAs quantum dots observed by differential transmission spectroscopy," *Tech. Dig., Quantum Electronics and Laser Science Conf. (QELS), Annual Conference on Lasers and Electro-Optics (CLEO) and the Quantum Electronics and Laser Science Conference (QELS)*, May 16-21, 2004, San Francisco, California.

K. L. Silverman, R. Mirin, S. T. Cundiff, A. G. Norman, "Direct Measurement of Polarization Resolved Transition Dipole Moment in InGaAs/GaAs Quantum Dots," *Appl. Phys. Lett.*, Vol. 82, No. 25, pp. 4552-4554 (23-Jun-2003).

Semiconductor Growth and Devices

Technical Contact:
Kris Bertness

Staff-Years (FY2004):
2 professionals
1 post-doctoral researcher
2 students

Goals

Develop measurement methods and provide data to support the efficient manufacture of semiconductor optoelectronic devices. Provide advanced materials and devices to support research in industry, other parts of NIST, universities and government laboratories.

Customer Needs

The continued growth of the U.S. optoelectronics industry is dependent on the high-yield manufacture of devices with smaller dimensions and tighter specifications. Compound semiconductor materials form the basis for LEDs, lasers, photodetectors, and modulators critical to optical communication, display, data storage, sensors, and many other applications. Many of these semiconductor devices now incorporate structures with a high degree of strain and nanostructures so small that the properties of the devices depend on their physical dimensions as well as the bulk materials properties. Measurements of starting materials, epitaxial layers, and nanostructured geometries must be supported by standard procedures and reference materials. Issues of materials purity and uniformity are at the foundation of device yield and performance. In addition, specialty devices are needed for use in metrology systems inside and outside of this project.

Technical Strategy

Structural characterization and control of quantum dots – Quantum dots are semiconductor structures with quantized energy levels that result in improved efficiency and tuning range for semiconductor lasers and less sensitivity to environmental changes for lasers and photodetectors. Dot formation is driven by strain during epitaxial crystal growth, but measuring the strain in structures less than 100 nm in lateral dimension presents new challenges. We are contributing to this field through studies correlating substrate preparation and growth parameters with dot density and size as measured by atomic force microscopy (AFM). We are also evaluating the shape of the dots and strain in the region of the dots with transmission electron microscopy (TEM). In addition, we are studying ways to control quantum dot growth and improve uniformity using strain.

PLAN: We will examine the influence of strain on formation and uniformity of quantum dots. We will evaluate AFM imaging of cleaved edges for measuring strain in stacked dots. We will publish our results on the influence of growth parameters on the lateral uniformity of quantum-dot growth.

Semiconductor quantum nanowire development – Semiconductor nanowires made from group III-nitrides are showing great promise for the next generation of high-efficiency, miniature light sources. Several research laboratories worldwide have demonstrated optically pumped lasing action in group III-nitride nanowires. To accelerate and support commercial development of these materials, we are pursuing fundamental studies of crystal growth for nanowires made of GaN, AlN and related alloys. The wires are characterized with high-resolution electron microscopy and scanning-probe microscopy, and we are also exploring new characterization methods. We supply materials to collaborators inside and outside of NIST, particularly the Optical Materials Metrology Project.

PLAN: Fabricate and characterize p-n heterostructure nanowires in the AlGaInN alloy system as progress towards the goal of demonstrating an electrically pumped group III-nitride nanowire laser.

Semiconductor composition standards development – Inaccuracy of semiconductor composition measurement has been an impediment to achieving consistency of device performance across production lines. It has also inhibited the collection of sufficiently accurate materials parameters for use in the simulation of devices, which is critical to fast product cycle times. A goal of this project is to develop certification techniques for standard reference materials having composition uncertainty specified to a level over ten times lower than that of techniques currently in use by industry. Our approach is to combine conventional methods of determination of composition (photoluminescence (PL), photo-reflectance (PR), and x-ray diffraction (XRD)) with less common methods (*in situ* monitoring, electron microprobe analysis (EMPA), and inductively coupled plasma optical-emission spectroscopy (ICP-OES)) to enable certification of alloy composition. This program is the basis for the production of standard reference materials (SRMs) in the AlGaAs and AlInGaN alloy systems. As part of this research, we have quantified error sources and accuracy limits of the indirect composition measurement techniques currently in use by industry, specifically PL and XRD.

PLAN: Offer AlGaAs composition standards for nominal Al mole fraction x=0.2 and x=0.3 with relative mole fraction uncertainty of ± 2 % or less. Investigate the precision of measurement techniques necessary for the development of AlGaN composition standards. Publish the results of ICP-OES and specimen storage studies.

Source gas purity measurement – Contamination is a serious problem in phosphine, arsine, silane, ammonia, and similar gases used in the epitaxial growth of high-purity semiconductor layers. Semiconductor device manufacturers have expressed frustration with the irreproducibility of purity of source material from vendor lot to vendor lot. The critical concentrations of the impurities are not well known; however, it is believed that >10 nmol/mol oxygen or water in most process gases is undesirable. In collaboration with researchers in the NIST Chemical Science and Technology Laboratory, this project has developed a cavity-ring-down spectroscopic (CRDS) technique to measure impurities with very low concentrations in semiconductor source gases. The advantages of this technique are that its accuracy relies primarily on accurate time measurement and detector linearity, rather than measurement of absolute light intensities, and it is insensitive to absorption outside the cavity. We are using our system to measure the lineshape, absorption coefficients, and frequency of optical transitions for water, phosphine and ammonia in the vicinity of 935 nm and 1380 nm. This information is critical to facilitate the use of high-sensitivity spectroscopy techniques in these gases. The CRDS capability should ultimately lead to improvements in semiconductor source gas purity, which will allow crystal growers to choose less expensive growth conditions without sacrificing optical emission efficiency and yield in LEDs, semiconductor lasers, and photodetectors.

PLAN: Identify optimal spectral regions for measurement of water in phosphine and ammonia. Increase the sensitivity of our CRDS apparatus to water detection in these gases through the use of stronger absorption lines at longer wavelengths.

Nanoscale strain measurement – Native-oxide layers have a significant impact on compound semiconductor photonic devices due to their ability to provide both electrical and optical confinement. In particular, the use of AlGaAs oxide apertures in VCSELs, which make up a large fraction of the telecommunications laser market, has resulted in record low threshold currents and high efficiencies. However, AlGaAs layers undergo a relatively large contraction during oxidation, resulting in strain sufficient to cause device delamination and failure. To address this issue we are collaborating with the NIST Materials Science and Engineering Laboratory on imaging strain in these materials using electron backscatter diffraction (EBSD) and high-resolution convergent-beam electron diffraction (CBED). These techniques allow the identification of strains as small as 0.02 %, with lateral resolution on a nanometer scale. We are pursuing means to minimize the strain through appropriate choice of materials and oxidation conditions.

PLAN: Publish the results of our studies on the kinetics and thermodynamics of native oxides including techniques to minimize strain in devices employing them. Also publish our work on measurements of strain adjacent oxide layers in VCSEL structures.

ACCOMPLISHMENTS

■ **Quantum-dot distribution nonuniformities measured** – We demonstrated that large lateral variations in dot density and height occur for both MBE and MOCVD grown quantum dots. Atomic force microscopy (AFM) images were taken at a programmed array of points across the surface of 50 mm wafers, and systematic analysis of the images was used to determine the average dot density and height from each image. For dots grown at temperatures between 500° C and 530 °C, the density was found to vary up to 80 % across the central 2 x 2 cm² region of a wafer, with the standard deviation of the dot density being up to 50 % of the average. The best samples analyzed had standard deviations in dot density of 5 %. Variations in the dot height were smaller, typically <10 %. We found that buffer layer roughness and dot growth temperature do not control the nonuniformity Substrate rotation speed was found to contribute to, but not completely control, the dot uniformity.

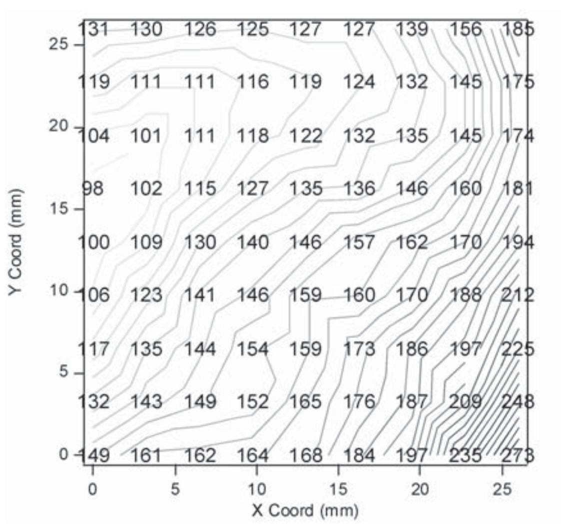

Figure 1. Contour plot of InGaAs quantum dot density on a typical specimen.

■ **GaN epilayer and nanocolumn growth capability** – We extended the semiconductor epitaxial growth capabilities at NIST by demonstrating the growth of group III-nitride layers and nanocolumns. Several single-crystal films were grown on silicon substrates. X-ray diffraction (XRD), optical emission, and carrier concentration measurements indicate the films were of high quality. We demonstrated growth of AlN and GaN nanocolumns using molecular beam epitaxy with ammonia as a nitrogen source. Field-emission scanning electron microscopy (FESEM) and atomic force microscopy (AFM) indicate that the column diameters range from 12 nm to 30 nm. The growth temperature of the AlN buffer layer was shown to be the critical process parameter for the growth of nanocolumns. We also found that physically isolated nanowires do not form when being grown with ammonia rather than with a plasma-assisted nitrogen source.

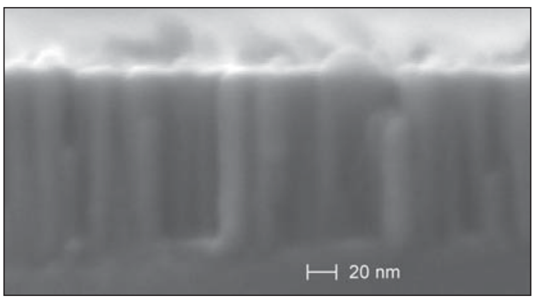

Figure 2. AlN nanocolumns grown at 600 ºC. Columns are 15–20 nm in diameter.

■ **AlGaAs standards production runs and certifications** – We have completed crystal growth runs and preliminary tests for three batches of AlGaAs SRMs with Al mole fraction near 0.2 and 0.3. In addition, we have completed a study correlating ICP-OES measurements with our other methods and a study of storage condition effects on these materials.

■ **Ten-fold sensitivity improvement in phosphine purity measurement** – We have greatly improved the sensitivity limit of the measurement of water impurities in phosphine by using cavity ring-down spectroscopy (CRDS) to characterize the pressure and carrier gas effects on the shape of water absorption lines. Interference from neighboring phosphine lines limits the sensitivity of the CRDS system in the region of water absorption lines. Using the water line at 10667.76 cm^{-1} (937.4 nm), we decreased by approximately a factor of ten the CRDS detection limit to 50 nmol/mol water in phosphine relative to measurements using the stronger water line at 10687.36 cm^{-1} (935.7 nm). We also measured pressure-broadening coefficients for water absorption lines. More recently we have found that the water line at 10603.52 cm^{-1} (943.1 nm) has even less interference from phosphine, which should allow us to measure even lower water concentrations. We have demonstrated real-time measurement of water concentration in phosphine during the insertion of a gas purifier into the delivery line.

■ **Nanoscale strain measurements near native AlGaAs oxides** – We have made measurements of strain fields in GaAs adjacent to buried, partially oxidized AlGaAs layers. The oxidation of AlGaAs is accompanied by volumetric contraction of up to 7 % and can lead to device failure. The strain measurements were made in a field-emission scanning electron microscope with the electron-backscatter diffraction (EBSD) technique, which has a resolution smaller than 50 nm. From the EBSD maps it was found that the strain is concentrated on the side of the layer closest to the substrate, as might be expected since the substrate constrains the layers. The strain was also found to be largest slightly behind the oxide growth front. This is consistent with thermodynamic calculations performed with collaborators at the Colorado School of Mines, which show that a narrow As-containing region exists immediately behind the oxide interface. This narrow region does not contract as the subsequent As-depleted regions of the oxide do.

■ **High-uniformity InGaAs photodiodes fabricated** – We produced highly uniform InGaAs photodiode prototypes for potential use in laser power calibration systems. The InGaAs semiconductor layers were grown with molecular beam epitaxy, processed into 5 x 5 mm^2 diodes and tested. The prototype photodiodes have properties similar to large-area commercial photodiodes, with high spectral responsivity (0.7 A/W without anti-reflection coating, equivalent to 0.95 A/W with coating), 1 % uniformity in spectral response over an area of at least 16 mm^2, and shunt resistance of 30 to 60 kΩ. The commercial suppliers of InGaAs diodes have been sporadic in their production of these products and have not been capable of meeting the more demanding specifications on a regular basis.

Key Collaborations

Matheson Tri-gas – Experiments on water impurity measurements in phosphine and other gases

Sandia National Laboratory – Study of MOCVD quantum dot uniformity

Agilent – Study of AlGaAs oxidation kinetics

IQE – Study of strain adjacent oxidized AlGaAs layers in VCSEL structures

NASA Goddard Space Flight Center – Experiments on GaN nanocolumns for photocathode applications

National Renewable Energy Laboratory – Storage studies for compound semiconductor materials

NIST Division 852 – Photoluminescence and photoreflectance measurements for AlGaAs composition and strain

NIST Division 853 – Electron backscatter diffraction and convergent beam electron diffraction for measurement of strain in compound semiconductor nanostructures

Recent Publications

S. Y. Lehman, K. A. Bertness, J. T. Hodges, "Optimal Spectral Region for Real-Time Monitoring of Sub-ppm Levels of Water In Phosphine Using Cavity Ring-Down Spectroscopy," *Journal of Crystal Growth*, Vol. 261, pp. 225-230 (01-Jan-2004).

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K. A. Bertness, S. Y. Lehman, J. T. Hodges, "Moisture Measurements in Semiconductor Process Gases Using Cavity Ring-down Spectroscopy," *Gases & Technology Magazine*, pp. 21-25 (01-Mar-2003).

K. A. Bertness, L. H. Robins, J. T. Armstrong, R. B. Marinenko, A. J. Paul, M. L. Salit, "Composition Standards for III-V Semiconductor Epitaxial Films," *Tech. Dig., CS-MAX 2002, Compound Semiconductor Mfg. Expo*, Nov 11-13, 2002, San Jose, California, pp. 42-44 (11-Nov-2002).

T. E. Harvey, K. A. Bertness, R. K. Hickernell, C. M. Wang, J. D. Splett, "Accuracy of AlGaAs Growth Rates and Composition Determination Using RHEED Oscillations," *J. Crystal Growth*, Vol. 251, pp. 73-79 (01-Jan-2003).

C. Fu, K. A. Bertness, C. M. Wang, "Effects of Noise Level in Fitting *In-situ* Optical Reflectance Spectroscopy Data," *J. Crystal Growth*, Vol. 251, pp. 118-123 (01-Jan-2003).

A. Roshko, K. A. Bertness, "Interlaboratory Comparison of InGaAsP *Ex-situ* Characterization," *J. Crystal Growth*, Vol. 250, pp. 223-228 (01-Jan-2003).

A. Roshko, K. A. Bertness, J. T. Armstrong, R. B. Marinenko, M. L. Salit, L. H. Robins, A. J. Paul, R. J. Matyi, "X-ray Diffraction, Photoluminescence and Composition Standards of Compound Semiconductors," *Physica Status Solidi*, Vol. 0, No. 3, pp. 992-997 (01-Jan-2003).

S. Y. Lehman, A. Roshko, R. Mirin, J. E. Bonevich, "Investigation of the Shape of InGaAs/GaAs Quantum Dots," *Proc., Mater. Res. Soc. Symp.*, Dec 02-06, 2002, Boston, Massachusetts, Vol. 737, pp. E13.40.1-E13.40.6 (01-Jan-2003).

L. H. Robins, J. T. Armstrong, R. B. Marinenko, A. J. Paul, J. J. Pellegrino, K. A. Bertness, "High-accuracy Determination of the Dependence of the Photoluminescence Emission Energy on Alloy Composition in $Al_xGa_{1-x}As$ Films," *J. Appl. Phys.*, Vol. 93, No. 7, pp. 3747-3759 (01-Apr-2003).

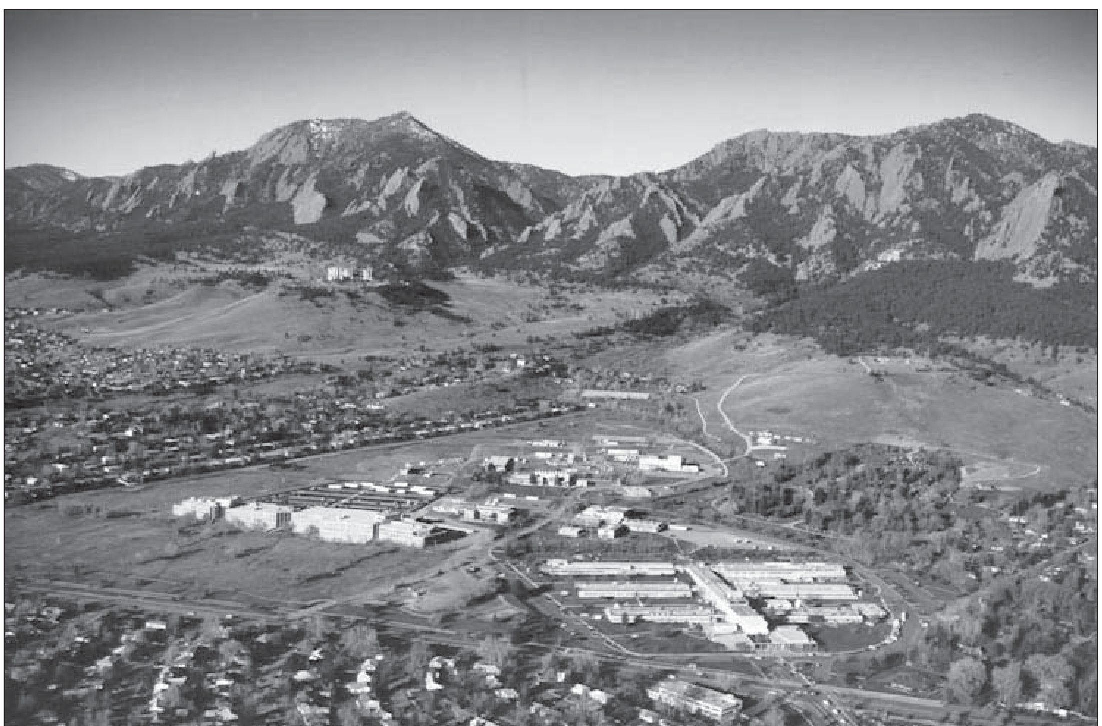
Appendix A: Major Laboratory Facilities

Semiconductor Growth and Optoelectronic Device Fabrication

The Division makes use of a gas-source molecular-beam epitaxy system and associated *in situ* and *ex situ* measurement equipment for III-V semiconductor growth and characterization. It also maintains a cleanroom facility for thin-film deposition, photolithography, and wet and dry etching. The facilities support the activities described above, particularly for the Optical Materials Metrology, Nanostructure Fabrication and Metrology, and Semiconductor Growth and Devices Projects.

Laser Power/Energy Detector Calibration Systems

The Optoelectronics Division has established and maintains several state-of-the-art measurement systems for calibrating most types of laser power and energy detectors. These measurement systems incorporate unique, specially designed, electrically calibrated, laser calorimeters that are used as primary standards. The calorimeters are used in conjunction with beamsplitter-based optical systems to provide measurement services for laser power and energy that cover a wide range of powers, energies, and wavelengths for detectors used with both cw and pulsed lasers. This assembly of laser power and energy detector calibration systems represents the best overall capability of this kind in the world. In many cases (*e.g.*, excimer laser measurements at 248 nm, 193 nm, and 157 nm), the Division has the only measurement capability in the world.



Appendix B: NRC Post-Doc and Other Research Opportunities

National Research Council Associateship Opportunities

The National Institute of Standards and Technology (NIST), in cooperation with the National Research Council (NRC), offers awards for post-doctoral research in many fields. These awards provide a select group of scientists and engineers an opportunity for research in many of the areas that are of deep concern to the scientific and technological community of the nation. NIST, with direct responsibilities for the nation's measurement network, involves its laboratories in the most modern developments in the physical, engineering, and mathematical sciences and the technological development that proceed from them. The Research Council, through its Associateship Programs office, conducts an annual national competition to recommend and make awards to outstanding scientists and engineers at the post-doctoral level for tenure as guest researchers at participating laboratories. The deadline for applications each year is February 1 for appointments beginning between July and the following January.

The objectives of the Programs are:

- To provide post-doctoral scientists and engineers of unusual promise and ability opportunities for research on problems, largely of their own choosing, that are compatible with the interest of the sponsoring laboratories.

- To contribute thereby to the overall efforts of the federal laboratories. Eligibility requirements include U.S. citizenship and receipt of Ph.D. within five years of application. NRC positions involve a two-year tenure at NIST, and the annual base salary for the 2005 program year is $55,700.

- For more detailed information, including instructions for applicants, please contact the Optoelectronics Division Office and request a copy of the NRC Postdoctoral Opportunities booklet. You also may visit the Optoelectronics Division web page (http://www.boulder.nist.gov/div815); or the NRC Research Associateship Program web page (http://www.nationalacademies.org/rap) to see a list of opportunities within our division.

Opportunities for the Year 2005 with the Optoelectronics Division Through the NRC Research Associateship Program:

Quantum Dot Morphology

Advisors: A. Roshko, K. A. Bertness

Quantum dots have attracted a great deal of interest because of their unique properties and possibilities for optoelectronic applications. However, control of dot density, composition, position, size, and shape remain major obstacles for many device applications. We invite proposals to address these issues through an investigation of quantum dot morphology as a function of growth parameters, such as temperature, rate, thickness, composition and dot stacking. Studies of the interrelations between these variables and strain state are also of interest. State-of-the-art molecular beam epitaxy with reflected high-energy electron diffraction, atomic-force microscopy, high-resolution x-ray diffraction, and transmission electron microscopy are available for analyzing quantum-dot distributions, heights, shapes, spacings, and strain fields. Correlation with optical properties, such as photoluminescence, is also of interest. The work will contribute to a more complete understanding of quantum-dot morphology, how it correlates with device performance, and how it can be controlled through the choice of growth conditions. It will also contribute to a larger effort at NIST on photodetectors and photon turnstiles.

Molecular Spectroscopy Using Ring-Down Cavities and its Application to Semiconductor Crystal Growth

Advisor: K. A. Bertness

Gases such as phosphine, ammonia, arsine, nitrogen, silane, and germane are widely used in semiconductor synthesis and processing. Most of these processes are highly sensitive to contamination, though the precise incorporation mechanisms and concentrations of concern are poorly known. We have developed cavity ring-down spectroscopy as a tool for high sensitivity measurements of impurities in gases along with the capability of using many of these gases in gas-source molecular-beam epitaxy growth. The system has a sensitivity for measuring water as an impurity down to approximately 30 ppb in phosphine and 10 ppb in nitrogen by use of laser light near 935 nm. We anticipate the availability of new laser sources in the next few years that will significantly enhance the flexibility and sensitivity of the instrument. Because of its fast time response, cavity ring-down spectroscopy is also useful for measuring time-dependent effects and confirming the efficacy of purifiers. We invite proposals extending the capability of the instrument to new impurities or host gases, for example, novel studies of correlations of gas properties with semiconductor crystal properties, and fundamental studies of the impurity incorporation process.

Photonic Crystals

Advisor: R. Mirin

Periodic arrays of dielectrics, metals, and semiconductors offer enormous potential for the realization of active and passive photonic bandgap crystals. Wavelength-scale periodic microstructuring can be used to create bands of allowed and forbidden optical propagation in direct analogy with well-established concepts of electronic bands in semiconductors. Photonic crystals may be used to control the rate of spontaneous emission of an active center by defining the allowed optical frequencies it may couple to — this may even be limited to a single optical mode. Line defects introduced into photonic crystals can produce three-dimensional waveguide structures exhibiting nearly zero loss with 90-degree bends. Various embodiments of photonic bandgap crystals are being considered which encompass oxide, semiconductor, ferroelectric, and ferromagnetic materials structured by methods of plasma deposition, epitaxial growth, wafer bonding, heterogeneous integration, and integration with optical MEMS. These structures are also envisioned to play a significant future role in advanced integrated optics for optical wavelength-division multiplexing, high-speed modulators, and high-extinction switches.

Semiconductor Quantum Optics

Advisor: R. Mirin

We are developing a regulated source of single photons by fabricating a single-photon turnstile with a single quantum dot. Our goals include spontaneous emission control and delivery of the individual photons to any other on-chip location through photonic crystal waveguides. Important technologies for this project include microcavities, microdisks, photonic crystals, and nonlinear optics. We invite experimental and/or theoretical proposals that can complement and expand on this ongoing effort. Available resources include epitaxial semiconductor growth, e-beam lithography, fabrication facilities, and finite – difference time – domain software for electromagnetic modeling.

Optical Spectroscopy of Quantum Dots

Advisor: R. Mirin

Self-assembled semiconductor quantum dots have been demonstrated for many optoelectronic devices (lasers, optical amplifiers, photodetectors) and proposed for novel applications such as quantum computing. However, there is still a lack of fundamental knowledge about the optical and electronic properties of these quantum dots, such as homogeneous linewidth, oscillator strength, coupling, carrier escape mechanisms, etc., especially at the level of single quantum dots. We invite proposals that will investigate these or other fundamental characteristics of self-assembled quantum dots.

MBE Growth of Quantum Dots

Advisor: R. Mirin

We are developing single-photon sources based on epitaxially grown single quantum dots. Many quantum dots are deposited during growth, and individual dots are isolated by masking and etching. The goal of this project is to use novel methods of controlling the exact placement and size of the quantum dots. This will enable schemes of coupling two or more quantum dots for applications in quantum information and quantum optics.

Compact Laser Technology for Optical Signal Processing and Free-Space Optical Communications Technology

Advisors: J. B. Schlager, N. A. Sanford

We are performing studies of ultra-low-jitter optical pulse generation and low-noise, narrow optical linewidth generation using NIST's compact rare-earth-doped glass waveguide technology. Applications include ultrafast all-optical analog-to-digital conversion systems, coherent optical signal processing and communication, LIDAR, and laser vibrometry. This work involves ongoing development and optimization of NIST's rare-earth-doped glass waveguide laser technology (Er/Yb,1550 nm; Nd, Yb, 1000 nm) as well as NIST's semiconductor saturable absorber technology. Laser stabilization to external references and metrology to assess laser performance will play crucial roles in this development.

Nanoscopic Wide-Bandgap Materials Characterization by CW and Ultrafast Nonlinear Optics

Advisor: N. A. Sanford

Near-field and confocal microscopy provide unique methods of characterizing a wide variety of semiconductor, dielectric, and hybrid optoelectronic materials and interfaces. We are developing methods of nanoscopic two-photon spectroscopy and nonlinear optics for examining local structural and electronic properties of the wide-bandgap III-nitride alloy semiconductors. The techniques include ultraviolet (UV) second-harmonic generation in addition to cw and time-resolved, two-photon UV spectroscopy that employ NSOM and confocal techniques. We are particularly interested in the study of local defects, polytyping, inversion domains, and alloy segregation; spectroscopy on the scale of defect separation (roughly 100 nm); and ultrafast processes involving interactions with strong static polarization fields in these materials. The spectroscopic results are correlated with x-ray diffraction imaging, high-resolution cathodoluminescence, and TEM.

Metrology and Prototyping of Wide-Band-Gap Semiconductor Quantum Nanowire Structures and Devices

Advisors: N. A. Sanford, A. Roshko, K. Bertness

Semiconductor quantum nanowires offer new applications in areas such as chemical sensors, NEMs, nanolasers, and nanoscale thermoelectric devices. A key aspect of these structures that makes the research challenging and enables the utility of various nanowire devices is the fact that many physical phenomena do not scale from the macro to nano regimes. Our research is focused primarily on nanowires grown from wide-bandgap semiconductors including the group III-nitride (GaN, AlN, InN) and ZnO material systems. We are interested in a range of research topics, from the applied to the fundamental, covering such areas as understanding the evolution of the microstructure of nitride semiconductors; development of nanotemplates for patterned growth of nanowires; optimization of p-type doping in nanostructures; developing methods of making electrical contact to single nanowires or arrays of nanowires; and development of new measurement methods for quantifying nanoscale piezoelectric, transport, and optoelectronic phenomena. Current device interests include nanowire lasers, photodetectors (primarily in the UV), UV and visible light emitters (*i.e.*, solid-state lighting), and field-emitting ion sources for mass spectrometry. We welcome proposals aimed at new technological aspects of semiconductor quantum nanowire research and application. Our characterization resources include triple-axis x-ray diffraction, atomic force microscopy, scanning electron microscopy, nonlinear optical characterization, near-field scanning optical microscopy, cw and time-resolved photoluminescence, device processing and electrical measurements. Opportunities exist for collaborative work within NIST for more specialized characterization such as TEM, field-emission SEM, STM, cathodoluminescence, and nanoscale electrical and thermal measurements.

Our existing programs make use of gas-source molecular beam epitaxy growth of nitrides, phosphides, and arsenides with a focus on nanostructures. Also, a wide range of clean-room processing equipment is available in order to carry out prototyping of specialized nanostructures.

In-Situ Metrology of Epitaxial Crystal Growth for Semiconductor Optoelectronics

Advisors: K. A. Bertness, R. K. Hickernell

Semiconductor optoelectronic devices are being employed in a variety of applications, including telecommunications, computer interconnects, data storage, display, printing, and sensor systems. Most of these devices rely on accurate, reproducible epitaxial crystal growth; however, further reductions in growth cost will require further development of *in situ* and *ex situ* measurement tools. Our research focuses on optical in situ material probes (*i.e.*, pyrometry, atomic absorption spectroscopy, and broadband normal-incidence optical reflectance) correlated with reflectance high-energy electron diffraction, *ex situ* x-ray diffractometry, photoluminescence spectroscopy, optical reflectance, and extensive modeling capabilities. Other resources include in situ mass spectrometry, atomic force microscopy, transmission electron microscopy, electrochemical profiling, and clean room facilities for processing test and device structures. We also examine the practical utility of various measurement tools through the growth of device structures, with emphasis placed on vertical-cavity surface-emitting lasers, in-plane lasers, quantum-dot lasers, and saturable Bragg absorbers.

Flat Panel Display Metrology

Advisors: E. F. Kelley (Boulder), P. A. Boynton (Gaithersburg)

NIST's flat panel display laboratory serves the display industry by developing and quantifying good electronic display metrology for industrial use. With the explosion of the information age, the Internet, and e-commerce, the use of flat panel displays has become a growing need for US industries. Good display measurement methods are needed because of the fierce competition between technologies, allowing consumers to compare features of displays accurately and fairly. NIST is doing research in: (1) equipment on improving measurements made on displays; (2) development of display metrology with various standards organizations; (3) development of display metrology assessment methods and equipment to provide guidance for the implementation of good measurement methods in the display industry; and (4) display reflectance characterization, measurements, and modeling using the bi-directional reflectance distribution function. Opportunities are available at both Boulder and Gaithersburg campuses.

High-Speed Optoelectronics Measurements

Advisors: P. D. Hale, T. S. Clement, D. F. Williams

Increasing data rates and bandwidths of optical telecommunications, cable television systems, remote microwave antenna links, and computer data interconnections all require advanced techniques for accurately determining optical transmitter and receiver frequency response in both magnitude and phase. Methods being investigated at NIST include heterodyne and ultrashort pulse technologies. Current research focuses on fully calibratable measurement of frequency response with low uncertainty to 110 GHz, and extension to 400 GHz in the near future. We are especially interested in the measurement of response phase with low uncertainty using high-speed sampling techniques and in methods for verifying these measurements. Future calibration artifacts will require fabrication of ultrafast photodetectors. We are also interested in theoretical studies of the modulation characteristics, frequency response, spectral response, saturation, and electrical characteristics of optical receivers that would further enhance our metrology effort.

High-Speed Optical Receivers and Optoelectronic Integrated Circuits

Advisors: P. D. Hale, T. S. Clement, R. P. Mirin, D. F. Williams

The need for ever smaller size and increased bandwidth of optoelectronic devices is requiring these devices to be packaged in hybrid modules and optoelectronic integrated circuits. Characterization of the frequency response and electrical properties of these devices requires a change in measurement strategy away from coaxially connected modular devices to on wafer measurements. We are developing a new fully calibratable on-wafer measurement paradigm for calibrating optoelectronic and electronic devices to bandwidths exceeding 110 GHz. We are interested in fabricating new high-speed receivers that will be used as calibration artifacts in this new measurement strategy. Possible designs might include metal-semiconductor-metal photoconductive switches or p-i-n photodiodes grown in low-temperature GaAs or InGaAs. The work will result in artifacts that will be used to calibrate high-speed measurement equipment.

Ultrashort Optical Pulse Characterization for High-Speed Measurements

Advisors: T. S. Clement, P. D. Hale

Femtosecond lasers are currently being used in the metrology of high-speed optoelectronic devices. We need to develop accurate methods of characterizing the femtosecond laser pulse amplitude and phase, as well as jitter noise on a train of ultrashort pulses. Increasingly stringent requirements in modern optoelectronic systems require waveform characterization over five decades in the frequency domain. The pulses need to be characterized with high dynamic range (in magnitude and in time) to detect pedestals and other aberrations. Pulse jitter and phase noise also affect many applications, including optical sampling and communications network synchronization, and may need to be characterized to levels as low as 10 fs. The well-characterized pulses will be used as a source for optical receiver measurements, as a characterization pulse for electro-optic sampling of high-speed circuits and transmission lines, and for characterizing optical waveforms that are modulated at very high speeds. We are especially interested in increasing the bandwidth of frequency-response measurements to 110 GHz, where it will become necessary to de-convolve the effect of the optical pulse from the rest of the measurement.

Waveform Metrology

Advisors: P. D. Hale, T. S. Clement

Current techniques used by industry for characterizing digital waveforms, both electrical and optical, are qualitative at best. As a result, the specifications for test equipment and communication systems are conservative and are not well understood. For example, both the computer and communications industries need measurements of different types of jitter and inter-symbol interference because these effects could cause erroneous bit transmission. We have developed a world-class capability for characterizing and calibrating equipment used in the acquisition of high-speed waveforms. We are looking for proposals that will investigate calibrated waveform measurement and the quantitative study of waveform metrics that characterize parameters such as random jitter, inter-symbol interference, and eye margin.

Tunable Laser Ensemble Development for Laser Radiometry

Advisor: J. H. Lehman

The calibration of laser and optical fiber meters over wavelengths ranging from 200 nm to 1800 nm requires laser sources that are stable and broadly tunable, and have well defined optical properties (polarization, beam quality, etc.). Our goal is to go beyond merely demonstrating what wavelengths may be produced by novel methods. We will demonstrate a variety of sources that are continuously tunable over the entire wavelength of interest (200 nm to 1800 nm), and deliver the output of these sources to various laboratories using optical fiber. This will enable cost-efficient, routine, calibration services having low uncertainties. We may employ new methods and equipment or optimize existing methods and equipment to ensure that NIST can provide laser power measurement comparisons with standards laboratories around the world as well as with manufacturers of laser and optical fiber power measurement equipment. Several new projects are under consideration to provide novel, robust methods for the generation and transportation of tunable laser light.

Improved Standard Detectors for Laser Power and Energy Measurements

Advisor: J. H. Lehman

Several areas of research are presently being pursued; improved coatings for thermal detectors, UV detectors resistant to damage and aging, and improved transfer standards for pulsed-laser radiation measurements. In each case, our goal is to develop and maintain optical detectors that are traceable to electrical standards for the purpose of maintaining calibration services in the area of laser power and energy measurements. Nearly all of the primary standards for laser power and energy measurements at NIST are based on thermal detectors. We also employ a variety of photodiode-based detectors as transfer standards for routine laser power calibrations for our customers. In each of these areas, the practical matters of providing cost-efficient, routine calibrations having low uncertainties must be considered. Topics of interest are new technologies and/or methods for developing and transferring detector-calibration information from one area to another.

Deep-Ultraviolet Laser Metrology

Advisors: C. L. Cromer, M. L. Dowell

In recent years, ultraviolet (UV) lasers — specifically excimer lasers — have found increased use in a variety of industrial and medical applications. For example, the most recent generation of optical lithography tools employ KrF (248 nm) excimer lasers for manufacturing computer chips with features sizes below 0.2 m. Future generations will incorporate ArF (193 nm) and F2 (157 nm) excimer lasers as the semiconductor community pushes toward feature sizes of less than 0.1 nm. In addition, ArF excimer lasers are utilized in photorefractive keratectomy and laser-assisted stomal in-situ keratomileusis procedures for vision correction. Accurate measurements of laser pulse energy, total dose energy, and laser beam profile are critical in all of these applications. Furthermore, accurate materials characterization procedures are necessary to improve, model, and monitor tool performance. Our work includes the development of high-accuracy UV primary- and transfer-standard detectors, beam profile characterization, laser power, energy and dose-measurement services.

Chromatic Dispersion Metrology

Advisor: P. A. Williams

In optical telecommunications systems, chromatic dispersion (CD) causes the optical data pulses to spread in time, limiting the data transmission rate. This is dealt with by tailoring the waveguide dispersion of the transmission fiber or by adding a compensating element of opposite dispersion at the end of the transmission link. Some compensating elements can have important, but spectrally narrow, group delay features that are difficult to measure. Typical CD measurement systems are based on a radio-frequency phase-shift technique or low-coherence interferometry. We invite proposals on such topics as improvements to existing CD measurement techniques (accuracy or resolution improvements), new measurement techniques, or development of fundamental dispersion standards (for example, using molecular absorption lines to give a theoretically predictable dispersion).

Polarization-Mode Dispersion Metrology

Advisor: P. A. Williams

In high-speed optical fiber telecommunications, the data rate can be limited by a critical parameter in the fibers and related components: Polarization-mode dispersion (PMD). This is especially true as data rates approach 40 Gigabits per second. PMD is a polarization-dependent group delay caused by birefringence and results in spreading of optical pulses in a statistical way that confounds passive compensation. This statistical nature makes PMD a complex (but interesting) topic with many measurement subtleties. Most recently, issues of active compensation and emulation as well as higher-order effects require improvements in PMD metrology. We solicit proposals on such topics as improvement to PMD measurement techniques (better spectral and temporal resolution), measurements of higher-order PMD, and metrology in support of PMD compensation.

Low-Coherence Interferometry for Fiber Optic and Component Metrology

Advisor: S. D. Dyer

Low-coherence interferometry is a valuable technique for measuring the dispersion and spectral characteristics of optical fiber and components. We are interested in applying low-coherence interferometry to simultaneously measure the key characteristics of optical components, including chromatic dispersion, polarization-mode dispersion and polarization-dependent loss. We are also interested in improvements that will enable us to obtain spatially resolved measurements of dispersion, polarization-mode dispersion, and other characteristics. This would be particularly valuable for characterizing components that consist of multiple elements; using low-coherence interferometry we can determine the contributions of each individual element in the device. Other potential new areas of research include the application of low-coherence techniques to the characterization of novel fibers and components, such as holey fiber, and to the characterization of active elements such as erbium fiber amplifiers, Raman amplifiers, and semiconductor optical amplifiers. We are also interested in developing frequency-domain measurements in which a swept laser source is used in place of the conventional low-coherence source.

Optical Coherence Tomography

Advisors: S. D. Dyer, P. A. Williams, J. P. Dunkers

Optical coherence tomography (OCT) is an exciting technique to achieve high-resolution, three-dimensional, in vivo images of human tissue. OCT has excellent spatial resolution (1–10 micrometers), which is two orders of magnitude better than ultrasound. OCT has applications ranging from early detection of glaucoma to measuring the morphology of the arterial plaques that may be responsible for 70 % of heart attacks. We are interested in developing accurate, fast, high-resolution OCT measurements. This includes comparing the speed and signal-to-noise ratio of conventional (broadband source) OCT with that of swept-frequency laser OCT configurations and providing wavelength metrology for swept-frequency lasers. The accuracy of an OCT distance measurement is limited by the scattering, absorption, dispersion, and birefringence of the tissue, as well as the lack of high-accuracy data on the refractive indices of various human tissues. The refractive index is important because OCT measures the optical path length, which is the product of the layer thickness with the group refractive index. To address this problem, we are interested in developing techniques to simultaneously measure both thickness and refractive index. We are also interested in developing calibration techniques for OCT thickness measurements and for general tissue refractive index measurements. Another area of interest is developing fast measurements for optical coherence microscopy, where a lens with high-numerical aperture is used to further improve the OCT measurement resolution.

Fiber-Optic Sensor Metrology

Advisor: S. D. Dyer

Fiber-optic sensors are lightweight, tiny, and flexible, with low power requirements and large dynamic range. They can detect a variety of measurands, including strain, temperature, pressure, and electromagnetic quantities. Much of our research focuses on fiber Bragg gratings (FBGs) for strain, temperature, and pressure sensing. We are interested in developing high-accuracy wavelength measurements for sensor calibration. Because hysteresis and nonlinearity due to the FBG's polymer coating and adhesives affects sensor calibration, we are also interested in novel measurement techniques to characterize these effects. Other important topics include techniques for distributed sensing with high spatial resolution (less than 100 micrometers), and understanding and improving the process of writing Bragg gratings in optical fibers.

Nonlinear Properties of Optical Fiber and Components

Advisor: N. R. Newbury

As the capacity of communication systems increases both through higher bit rates and an increased use of wavelength-division multiplexing, optical nonlinearities are becoming increasingly important. These nonlinearities can be both detrimental and beneficial to the system performance. Self-phase modulation, cross-phase modulation, or four-wave mixing can limit system performance, while Raman amplification or intentional wavelength conversion through four-wave mixing can enhance system performance. We invite proposals for new methods for characterizing and exploring these nonlinear effects. Examples include developing basic metrology for the nonlinear coefficient n2, including its polarization and temporal properties, developing optical methods for characterizing the gain and noise properties of distributed Raman amplifiers, and exploring the characteristics and potential uses of highly nonlinear holey or photonic crystal fiber.

Supercontinuum Generation in Highly Nonlinear Optical Fiber

Advisor: N. R. Newbury

A supercontinuum of light that spans over an octave in frequency can be generated by launching pulses from femtosecond lasers into highly nonlinear optical fiber. Through recently developed techniques, this supercontinuum can be phase-locked to a reference and thereby provide a stable frequency comb with a spacing equal to that of the laser repetition rate. These frequency combs have revolutionized optical frequency metrology since optical frequencies can now easily be measured relative to the time standard. We invite proposals that explore the generation, properties, and applications of the supercontinuum. We are particularly interested in the generation of stable frequency combs in the telecommunications band that could be used for wavelength metrology. Other examples of proposals include developing a better understanding of the noise properties of the supercontinuum, and exploring other uses of the frequency comb related to LIDAR or optical coherence tomography applications.

Wavelength Standards for Optical Communications

Advisor: S. L. Gilbert

Optical fiber communication systems are now incorporating wavelength division multiplexing (WDM); many wavelength channels in the near-infrared region can be transmitted on each optical fiber. Current WDM systems typically employ 50 or 100 GHz channel spacing (0.4 or 0.8-nm, respectively) in the 1540- to 1560-nm region; however, narrower channel spacing may be implemented soon. WDM will likely expand into other wavelength regions, possibly covering the entire range from about 1280–1630 nm. Wavelength standards are needed to set the absolute wavelength of these channels and avoid crosstalk. We invite proposals for the development of wavelength standards in the WDM region. Examples include high-accuracy standards for NIST internal calibration (possibly based on high-resolution spectroscopy and novel frequency comb techniques) and moderate-accuracy standards that can be used by industry over broad wavelength regions.

Fiber Bragg Gratings and Ultraviolet Photosensitivity

Advisor: S. L. Gilbert

Ultraviolet (UV) light can induce a permanent change in the refractive index of a glass material. This UV photosensitivity is very useful in fabricating novel integrated optic and fiber Bragg grating devices. Fiber Bragg gratings (wavelength-selective reflectors written into the core of optical fiber) are very useful as wavelength filters and dispersion compensators in the new wavelength-division multiplexed optical fiber communication systems. They also make excellent strain sensors that can be networked to obtain distributed strain measurements of large structures such as bridges and ships. Despite the development of numerous devices and techniques to control the phenomenon, a fundamental understanding of UV photosensitivity remains incomplete. We invite proposals on the study of UV photosensitivity or the development of new measurement methods for characterizing fiber Bragg grating devices.

Professional Research Experience Program (PREP)

The Professional Research Experience Program (PREP) is designed to provide valuable laboratory experience to undergraduate and graduate students from the University of Colorado at Boulder and from the Colorado School of Mines at Golden, and to recent Ph.D. recipients from these and other universities. Students and postdocs are employed by the University of Colorado or the Colorado School of Mines and normally carry out research at the NIST Boulder Laboratories.

Students are usually hired just before the spring, fall, or summer terms, and may be employed for one or more terms. Post-docs may begin any time during the year. Applications are accepted throughout the year.

NIST pays in-state tuition for PREP undergraduate students during the fall and spring semesters and an hourly wage. Graduate students receive in-state tuition and a stipend. Post-docs receive a stipend.

Eligibility requirements include U.S. citizenship or permanent residency and, for students, a minimum 3.0 GPA (grade point average).

An application form and further information are available from:

Phyllis Wright, Student Outreach Coordinator
NIST, MC 360
325 Broadway
Boulder, CO 80305
Phone: (303) 497-3244
Email: pkwright@boulder.nist.gov
http://www.boulder.nist.gov/exec/bdprepo.htm

Summer Undergraduate Research Fellowships (SURF)

The SURF NIST Boulder Program provides 12-week appointments for outstanding undergraduates to engage in state-of-the-art research with senior scientists and engineers in the unique research facilities at the NIST campus in Boulder, Colorado.

Eligibility requirements include U.S. citizenship or permanent residency, and undergraduates at a U.S. university or college with a technical major. A G.P.A. of 3.0/4.0 or better is recommended. They must be covered by a health insurance plan (either through school or family). Students with physics, materials science, chemistry, mathematics, computer science, or engineering majors are encouraged to apply. There may be research opportunities for students with other majors.

The program duration is May to August with adjustments to be made to accommodate specific academic schedules (e.g., quarter systems).

Application deadline is February 15. The student's university must submit a grant proposal that provides details about its academic programs and nominates one or more students. Each student must provide a transcript, two letters of recommendation, and a personal statement of interest.

Housing will be provided within easy walking distance of NIST.

Contact:

Ms. Phyllis Wright
NIST, Office of the Director
325 Broadway
Boulder, CO 80305-3328
Phone: 303-497-3244
Fax: 303-497-4062
e-mail: pkwright@boulder.nist.gov

Further information is available at http://SURF.Boulder.NIST.gov.

Appendix C: Conferences and Workshops

Laser Measurements Short Course

The Optoelectronics Division offers an annual short course on laser measurements. The 3½-day course emphasizes the concepts, techniques, and apparatus used in measuring laser parameters. A tour of the NIST laser measurement laboratories is included. The most comprehensive seminar of its type, this course is ideal for those who need to understand the characteristics of lasers and laser measurements or who are responsible for laser systems. The seminar is taught by laser experts from NIST, industry, and other government agencies, and is intended to meet the needs of metrologists, scientists, engineers, laboratory technicians, educators, managers, and planners involved in the use of laser systems. A degree in physics or engineering or equivalent experience is assumed, and some experience in the use of lasers is desired.

The Technical Program covers a wide range of topics, such as:

- **Laser Operation**
  Troubleshooting, alignment, cleaning of optics, general maintenance.
- **Optics for Laser Measurements**
  Lenses, spherical aberration, diffraction, laser beams, beam divergence, beamsplitters, detector linearity.
- **Attenuation Techniques**
  Filters, specular reflectors, diffuse reflectors, speckle statistics.
- **Basic Laser Power/Energy Standards**
  Calorimeter theory and design, data methods, volume absorbers, source standards, absolute quantum detectors.
- **Laser Power/Energy Measurement Techniques**
  Calorimetry, beamsplitter system, calibration system, power/energy measurements, documentation, automation.
- **Pulse Measurements**
  Pulse parameter definitions, energy measurements, waveform measurements, detector characterization, time-domain techniques, subnanosecond measurements, systems, calibrations.
- **Beam Profile Measurements**
  Beam divergence, detector effects, near field, far field, fluence.
- **Optical Fiber Power Measurements**
  Traceability, calibration system, measurement uncertainty, detector linearity, detector uniformity, tunable lasers, round robins, connector effects, international comparisons.
- **Diode Lasers**
  Temperature stability, frequency control, measurement of peak power and energy, beam focusing, beam uniformity, angular divergence.
- **Laser Measurements for Optical Communications**
  Absolute coupled average power, waveform shape, spectral behavior.
- **Statistics and Error Analysis**
  Errors, uncertainties, measurement process characterization, estimation, statistical control.

- **Laser Safety**
  Hazards to the eye, evaluation measurements, beam diagnostics for safety purposes, eye protectors.

The Laser Measurements Short Course is typically held the first week in August. Interested parties should consult the Optoelectronics Division Office or visit the Division Web page at http://www.boulder.nist.gov/div815/ for information about upcoming courses.

Symposium on Optical Fiber Measurements

The Optoelectronics Division, in cooperation with the Optical Society of America and the IEEE Lasers and Electro-Optics Society, organizes the biennial Symposium on Optical Fiber Measurements held in Boulder, Colorado in the fall of even-numbered years. Check the Division web page or call the Division Office for the date of the next Symposium. This Symposium is a 2½-day meeting devoted entirely to the topic of measurements on fiber, related components, and systems. It provides a forum for reporting the results of recent measurement research and an opportunity for discussions that can lead to further progress. It consists entirely of contributed and invited papers.

Experimental and analytical papers on any measurement aspect of guiding lightwave technology are solicited for the Symposium. Subjects and measurements include:

- **Optical Fibers**
  Telecom, sensors, fiber lasers/amplifiers
- **Integrated Optics**
  Planar waveguides, photonic crystals, MEMs
- **Components**
  Amplifiers, lasers, detectors, modulators, switches, couplers
- **Systems**
  Long haul, LANs/subscriber loops, WDM, TDM
- **Standards**
- **Field and laboratory instrumentation**
- **Examples of typical measurements include:**

Attenuation/loss	Four-wave mixing efficiency
Chromatic dispersion	Index of refraction profile
Crosstalk	Mode-field diameter
Cutoff wavelength	Nonlinear coefficients
Effective area	Polarization-dependent loss
Effective index	Polarization-mode dispersion

A limited number of Digests from previous Symposia are available, as well as a CD-ROM with collected papers from 1980–2000. For information on obtaining either, or for information on upcoming Symposia, please contact the Optoelectronics Division Office or visit our Web page, http://www.boulder.nist.gov/div815/.

Appendix D: Calibration Services

From optical lithography for semiconductor manufacturing to the micromachining of small structures such as ink-jet printer nozzles, lasers are finding their way into an increasingly diverse number of industrial applications. As this expansion continues, laser metrology will continue to become more important for improved in-line process control, increased yields, and laser safety. In support of these applications, the Optoelectronics Division provides calibrations services at laser power levels from nanowatts to kilowatts and pulse energy levels from femtojoules to megajoules. Wavelength ranges include the standard ultraviolet, visible, and near-infrared laser lines. In addition to standard laser lines, we have a tunable laser ensemble that can provide measurements of additional laser wavelengths upon request. Detailed information about the Division's calibration service capabilities is given in Tables 1 through 5. Other laser-related measurement services are available upon request and will be delivered at cost.

Laser	Wavelength	Power
HeCd	325 nm	1 nW – 50 mW
Argon	488 nm	1 nW – 6 W
	514 nm	1 nW – 10 W
	Other Argon wavelengths available, call for power levels.	
HeNe	633 nm	1 nW – 20 mW
Diode	830 nm	1 nW – 20 mW
Nd:YAG	1064 nm	1 nW – 450 W (6 kW off-site)
	1319 nm	1 µW – 50 mW
Erbium	1523 nm	1 µW – 30 mW
CO_2	10.6 µm	100 W – 1 kW (6 kW off-site)
Ti:Sapphire	700 nm – 1 µm	1 nW – 1 W
Additional dye laser wavelengths available, call for power levels		

Table 1. Laser power and energy calibration services for optoelectronic devices used with cw laser radiation.

Laser	Wavelength	Energy
Q-Switched Nd:YAG	1.06 µm	1 – 300 mJ/pulse (1 – 20 Hz) 1 mW to 6 W average
Low Level Nd:YAG	1.06 µm	10^{-4} – 10^{-8} W (peak) 10^{-11} – 10^{-15} J/pulse
KrF	248 nm	5 µJ/Pulse – 250 mJ/Pulse 50 µW – 7 W average
ArF	193 nm	5 µJ/Pulse – 5 mJ/Pulse 10 µW – 3 W average
F_2	157 nm	1 µJ/Pulse – 3 mJ/Pulse 1 µW – 1 W average

Table 2. Laser power and energy calibration services for optoelectronic devices used with pulsed-laser radiation.

Parameter	Wavelength	Range	Status
Optical Detector Spatial Uniformity	635, 850, 1300, and 1550 nm	Detector size: 1 mm – 17 cm Resolution: 0.1 mm	Special Test
Optical Detector Linearity	193, 248, and 1064 nm 10.6 µm	1 nJ/pulse – 10 mJ/pulse	Special Test

Table 3. Detector characterization services.

Parameter	Wavelength (nm)	Range	Status
Absolute Power Calibration	670, 780, 850, 980 1310, 1550	10 – 100 µW	Calibration Service
	980	1 – 200 mW	Special Test
Optical Fiber Power Meter Linearity	850, 1310, 1550	60 – 90 dB	Calibration Service
Optical Fiber Power Meter Spectral Responsivity	400 – 1700	< 2 % uncertainty	Calibration Service

Table 4. Optical fiber power meter measurement services.

Parameter	Wavelength	Range	Status
Optical Receiver Frequency Response (Magnitude)	1319 nm	300 kHz – 50 GHz	Special Test
	1550 nm	1 MHz – 50 GHz	Special Test
Optical Receiver Vector Frequency Response	1550 nm	200 MHz – 110 GHz	Special Test
Reference Receiver (Optical Oscilloscope) Vector Frequency Response	850 nm 1550 nm	100 fs impulse source	Special Test
Optical Modulation Response Transfer Standard	1319, 1550 nm	300 kHz –110 GHz	Special Test

Table 5. Temporal and frequency response measurements.

See http://www.boulder.nist.gov/div815/Calibrations/Calibrations.htm for more information.

For technical information contact:

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Sources, Detectors, and Displays Group
Optoelectronics Division
NIST 815.01
325 Broadway
Boulder, CO 80305
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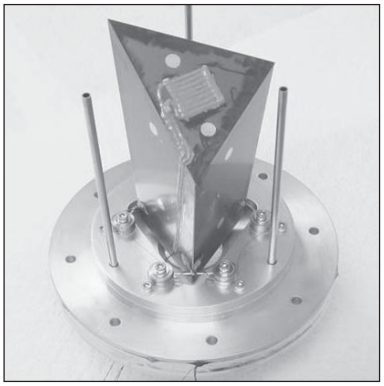
e-mail: marla.dowell@nist.gov

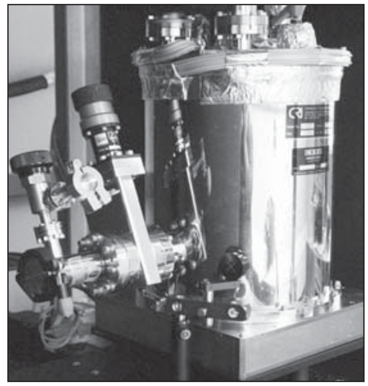
For scheduling and shipping information contact:

Maggie Mills, Measurement Services Coordinator
Optoelectronics Division
NIST 815.00
325 Broadway, 1-3055
Boulder, CO 80305
TEL: 303-497-4285
FAX: 303-497-4286
e-mail: caliopto@boulder.nist.gov

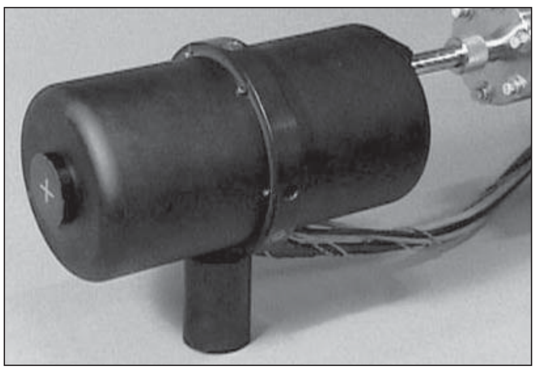
Primary Standards for Laser Radiometry



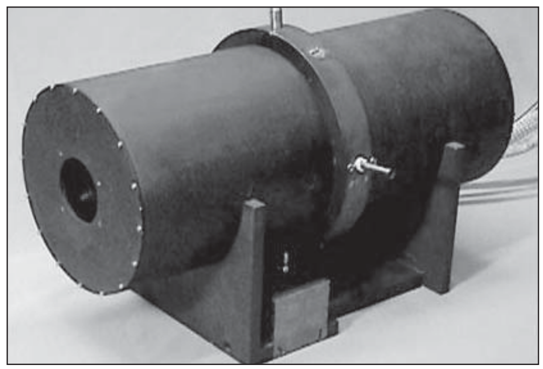
A SiC absorbing cavity for the 157 nm excimer laser calorimeter. Developed over the past few years, we now provide power and energy calibrations at this wavelength to support the semiconductor photolithography industry.



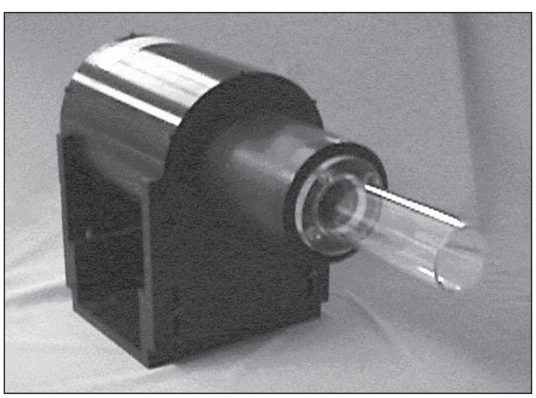
The Laser-Optimized Cryogenic Radiometer, developed in the late 1990s, and used for measurements of the highest accuracy with low-level cw lasers, 100 μW to 1 mW at wavelengths from 0.4 μm to 2 μm.



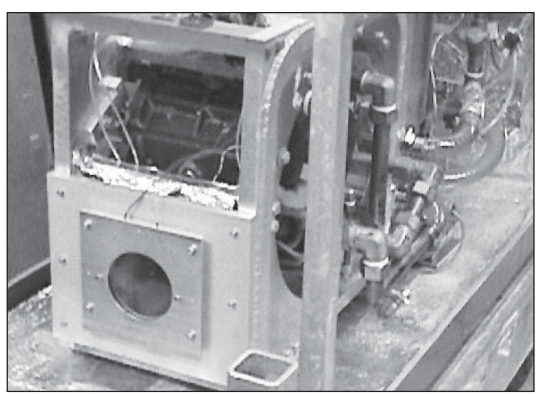
The C-Series Calorimeter, originally developed in the 1970s for use with cw lasers in the range from 50 μW to 1 W and 0.4 μm to 2 μm wavelength. Improved versions are in current use for calibrations.



The K-Series Calorimeter, developed in the 1970s, for high-power cw lasers in the range from 1 W to 1000 W and wavelengths from 0.4 μm to 20 μm. This calorimeter is in current use for calibrations.



Three versions of this standard are used for pulsed-laser calibrations. The Q-Series, developed in the 1980s, is used for 1.06 μm lasers. The QUV and QDUV calorimeters, developed in the 1990s, are in current use for calibrations at 248 nm and 193 nm, respectively. The new QVUV calorimeter is now on line for measurements at 157 nm.



The BB Calorimeter, developed around 1980 for the U.S. Air Force Metrology Laboratory, and is current use for cw lasers with power levels up to 100 kW.

Appendix E: Standard Reference Materials

Standard Reference Materials		
SRM Number	**Name**	**Brief Description**
	Composition Standards	
2841 **2842**	Composition Standards for Compound Semiconductors	***Under Development*** – Standards of epitaxial layers of compound semiconductors for application in calibration of analytical equipment (SIMS, EMPA, AES, XPS, etc.) and photoluminescence mapping. The first SRM (***planned release – 2005***) will be specimens of epitaxial layers of Al(x)Ga(1-x)As grown on GaAs substrates with x near 0.20 and 0.30 and uncertainty of ± 0.003. Additional mole fractions are also under development.
	Wavelength Calibration Standards	
2514	Wavelength Calibration Reference for 1560-1595 nm – Carbon Monoxide ($^{12}C^{16}O$)	Fiber-coupled molecular gas absorption cell with absorption lines in the WDM L-band between 1560 nm and 1595 nm
2515	Wavelength Calibration Reference for 1595-1630 nm – Carbon Monoxide ($^{13}C^{16}O$)	Fiber-coupled molecular gas absorption cell with absorption lines in the WDM L-band between 1595 nm and 1630 nm
2517a	High-Resolution Wavelength Calibration Reference for 1510-1540 nm – Acetylene ($^{12}C_2H_2$)	Fiber-coupled molecular gas absorption cell with narrow absorption lines between 1510 nm and 1540 nm
2519	Wavelength Reference Absorption Cell – Hydrogen Cyanide ($H^{13}C^{14}N$)	Fiber-coupled molecular gas absorption cell with absorption lines between 1530 nm and 1560 nm
	Polarization-Mode Dispersion Standards	
2518	Polarization-Mode Dispersion (mode coupled)	Simulates mode-coupled PMD in optical fiber; certified for mean DGD from 1480–1570 nm
2538	Polarization-Mode Dispersion (not mode coupled)	Simulates PMD in discrete components; certified for mean DGD from 1250–1650 nm
	Fiber and Fiber-Connector Geometry Standards	
2513	Mode Field Diameter Standard for Single-Mode Fiber	Optical fiber specimen with cleaved end and calibrated mode field diameter
2520	Optical Fiber Diameter Standard	Optical fiber specimen with cladding diameter values known to approximately ± 40 nm

Continued on next page

The following fiber and fiber connector geometry SRM's are produced by NIST's Precision Engineering Division (821.00)		
2522	Pin Gauge Standard for Optical Fiber Ferrules	Wire used to size bores of connector ferrules; diameter known to approximately ± 40 nm
2523	Optical Fiber Ferrule Geometry Standard	Ceramic connector ferrule with specified outside diameter and roundness
2553	Optical Fiber Coating Diameter	Glass rod with index of refraction n =1.504 and diameter of approximately 250 mm known within ±0.1 mm
2554	Optical Fiber Coating Diameter	Glass rod with index of refraction n =1.515 and diameter of approximately 250 mm known within ±0.1 mm
2555	Optical Fiber Coating Diameter	Glass rod with index of refraction n =1.535 and diameter of approximately 250 mm known within ±0.1 mm

Technical information on SRMs 2522, and 2523, 2553 , 2554, and 2555
can be obtained from:

Precision Engineering Division (821.00)
National Institute of Standards and Technology
100 Bureau Drive, Stop 8210, Met A109
Gaithersburg, MD 20899-8210
Phone: (301) 975-3463 Fax: (301) 869-0822

For additional technical information contact:

Optoelectronics Division (815.00)
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305
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Email: optoelectronics@boulder.nist.gov

For Detailed Ordering and Shipping Information contact:

Measurement Services Division – Standard Reference Materials
National Institute of Standards and Technology
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