NIST

National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce
January 2001
NISTIR 6602

Electronics and Electrical Engineering Laboratory

Optoelectronics Division

Programs, Activities, and Accomplishments

1901-2001
ENNIAL

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations, and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of five programmatic divisions, two matrix-managed offices, and a special unit concerned with magnetic metrology:

- Electricity Division
- Semiconductor Electronics Division
- Radio Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards
- Magnetics Group

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: The Optoelectronics Division supports the optoelectronics industry by providing new measurement techniques and standards to help characterize and assure the quality of its products. Examples shown here are laser power measurements for eye surgery, optical polarization changes in compact discs, minature laser sources for optical fiber telecommunications, and transmission losses for the many-kilometer lengths of optical fiber.

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U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary

Technology Administration
Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Karen H. Brown, Acting Director

Contents

Welcome

It's an exciting time for the optoelectronics industry, especially that portion of the industry concerned with optical communications. Sales of established components, for example optical fiber, are growing 30 to 40 % annually, and markets for some of the newer components used in high capacity communications systems are growing much faster. Attention from the financial community has been intense. Optoelectronics is widely discussed in the press, and companies in the field are becoming household names. Announcements of new optoelectronic products affect share prices, even of large companies, sometimes dramatically. According to a well-known market research firm, venture capital investments in optoelectronics companies were four-times larger in the first half of 2000 than they were in the same period of 1999.

Our job in the NIST Optoelectronics Division is to provide the industry with the measurement technology, standards, and traceability that it needs to continue to flourish. Industry studies have concluded that having a strong infrastructure is the key to the continued growth of the industry, and metrology is one of several key elements of that infrastructure.

Since the late 1960s, we have maintained the U.S. national standards for laser power and energy measurement and provided the industry with calibration services for detectors and power meters used with lasers. Since the late 1970s, we have worked with the optical communications industry to develop measurement methods and Standard Reference Materials (artifact standards) to support the specification of optical fiber and other components. Where possible, we also support the optical fiber sensor industry, the optical data storage industry, and the application of lasers and optoelectronics in the semiconductor and medical communities. To an increasing extent, we focus on the development of measurement technology for use in the manufacture of optoelectronic materials and components.

We are a team of about 60 scientists, engineers, and support staff, located in the NIST Boulder Laboratories, in Boulder, Colorado. We invite you to contact us to discuss our current work as well as your needs for metrology. You will find our names and points of contact on page *vi* and on our web site where you will also find additional information about our work and the services we provide to the industry.

Thank you for your interest in the Optoelectronics Division.

Gordon W. Day, Division Chief

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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, 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

During this year the Division was organized into four Groups. Three Groups focussed on the characterization of optoelectronic components -- the Sources and Detectors Group, the Fiber and Integrated Optics Group, and the Optical Components Group. The fourth Group--the Optoelectronic Manufacturing Group -- focussed on measurements that can lead to more efficient manufacturing of optoelectronic materials and components. (The Division has recently been reorganized for more efficient operations into the three groups indicated in the organizational chart on pg. vi.)

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 normally 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).

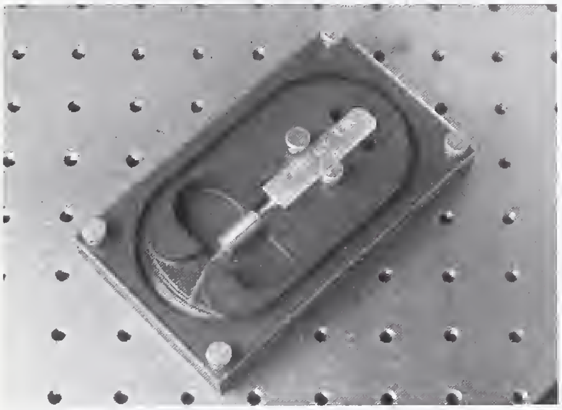
The Division and its predecessor organizations have been providing calibration services for the characterization of lasers and detectors since 1967, and each year conducts over 200 calibrations for about 50 customers. It also provides the industry with standard reference materials, which are artifact standards that can be used to calibrate a customer's 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 Optical Disc Manufacturer's Association (ODMA). 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.

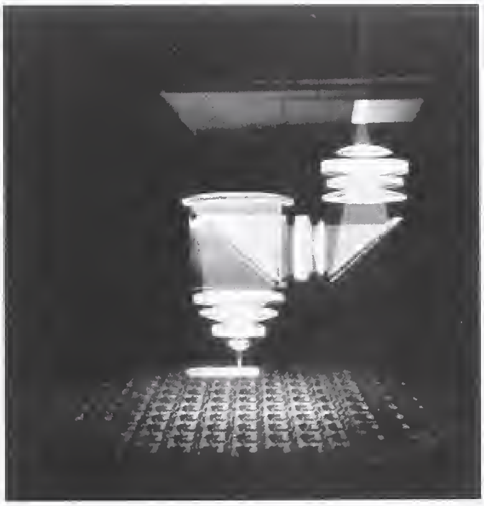
Courses and Conferences

The Division offers an annual Short Course on Laser Measurements and biennially organizes a major international conference on optoelectronic measurements, the Symposium on Optical Fiber Measurements.

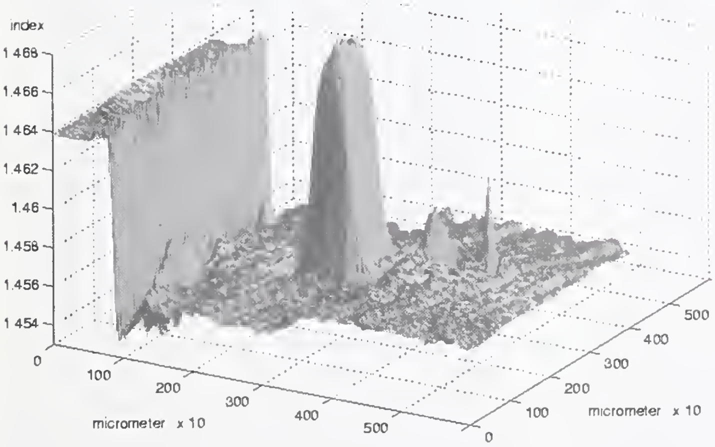
Research Highlights



PAST
Optical Fiber Diameter Standard: The first ever standard for optical fibers helped launch U.S. industry into a dominant role in the world's markets



PRESENT
The Optoelectronics Division provides the only laser power and energy calibration service for deep ultraviolet lithography used extensively by the semiconductor industry.



FUTURE
The Refracted Near Field method provides a new, more sensitive way to measure the index of refraction in integrated optics.

Optoelectronics Division

Division Office 815.00

Name	*Extension**
DAY, Gordon W., Chief	5204
CLARK, Alan F., Deputy Chief	5202
SMITH, Annie J., Secretary	5342
DERR, Linda S.	5123
McCOLSKEY, Kathy S., Administrative Officer	3288

Sources and Detectors (815.01)

SCOTT, Thomas R., (GL)	3651
SKINNER, Dorothy L., Secretary	3842
CASE, William E. (GS)	3741
CHRISTENSEN, David H	3354
CLEMENT, Tracy S. (PT)	3052
CROMER, Christopher L. (PL)	5620
DOWELL, Marla L. (PL)	7455
HALE, Paul D. (PL)	5367
JONES, Richard D.	3439
KEENAN, Darryl A.	5583
LAABS, Holger J. R. (GS)	7736
LEHMAN, John H.	3654
LEONHARDT, Rodney W.	5162
LI, Xiaoyu	3621
LIVIGNI, David J	5898
OBARSKI, Gregory E.	5747
PHELAN, Jr., Robert J. (GS)	3696
SIMPSON, Philip A. (CTR)	3789
TOBIAS, Iris L.	5253
VAYSHENKER, Igor	3394
WILLIAMS, Dylan (GS813)	3138
YANG, Shao	4168

NOTE:

Fiber and Integrated Optics (815.02)
This Group was incorporated into the Optical Components Group on October 22, 2000.

Legend:

CTR = Contractor
GL = Group Leader
GS = Guest Scientist
PD = Postdoctoral Appointment
PL = Project Leader
PT = Part Time
S = Student

*Telephone numbers are: (303) 497-XXXX, (the four digit extension as indicated)

Optical Components (815.03)

GILBERT, Sarah L., (GL)	3120
SKINNER, Dorothy, Secretary	3842
CRAIG, Rex M.	3359
DENNIS, Tasshi (PD)	3507
DRAPELA, Timothy J.	5858
DYER, Shellee D.	7463
ESPEJO, Robert J. (S)	7630
ETZEL, Shelley M. (PT)	3287
FRANZEN, Douglas L. (CTR)	3346
JACOBSEN, Eric R. (S)	7386
KUNKEL, Kari (S)	7630
RABIN, Michael W. (S)	3021
ROSE, Allen H. (PL)	5599
SORNSIN, Elizabeth (PD)	7612
SWANN, William C.	7381
WILLIAMS, Paul A.	3805
YOUNG, Matt (GS)	

Optoelectronic Manufacturing (815.04)

HICKERNELL, Robert K. (GL)	3455
REPETTO, M. Francesca, Secy	5187
BENSON, Robert G. (S)	7953
BERTNESS, Kristine A. (PL)	5069
CALLICOAT, Bert (PREP PD)	5952
CHEN, Ye (Mike) (S)	5164
FU, Chih-Chiang (S)	5572
HARVEY, Todd	3340
KIM, Chulsoo (PD)	3942
KLEIN, Benjamin (S)	7460
LEHMAN, Susan Y. (CTR)	7554
LESTER, Jacob (S)	7368
MIRIN, Richard P. (PL)	7955
ROSHKO, Alexana	5420
SANFORD, Norman A. (PL)	5239
SCHLAGER, John B.	3542
SILVERMAN, Kevin L.	7948

CW Laser Radiometry

Technical Contact:
Christopher L. Cromer

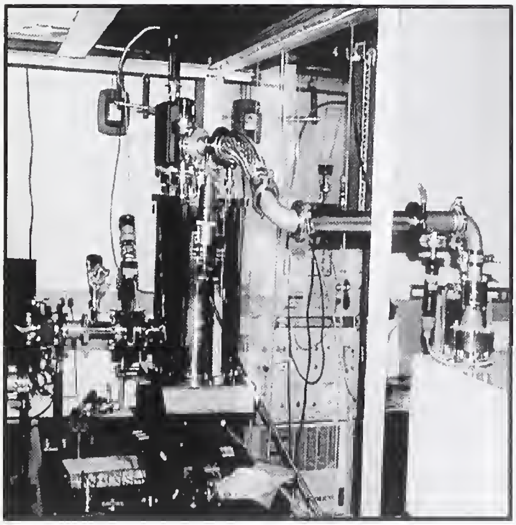
Staff-Years:
4.5 professionals
1.0 technician
2.0 contractors

Funding Sources:
NIST (77 %)
Other Government Agencies (18 %)
Calibration fees (5 %)

Parent Program:
Optoelectronics

Project 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 (e.g., spectral responsivity, linearity, etc.).



The Optoelectronics Divisions Laser Optimized Cryogenic Radiometer (LOCR). The radiometer uses electrical substitution techniques at liquid Helium temperature to provide the highest accuracy laser and optical fiber power measurements traceable to Silicon (SI) units.

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 optoelectronic 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 uniformity of laser power meters and detectors. In support of source characterization, measurement methods are developed to evaluate and characterize beam intensity profile and propagation of laser beams. Project members participate in national and international standards committees developing standards for laser safety, laser radiation measurements (such as beam profile and pointing stability), 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 tunable laser systems for laser power and energy measurement systems.

Technical Strategy

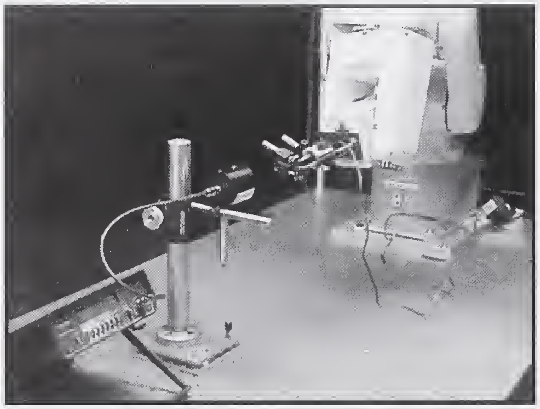
Meeting the needs of the laser and optoelectronics industries and anticipating emerging technologies requires investigation and development of improved measurement methods and instrumentation for high-accuracy laser metrology over a wide range of powers, energies, and wavelengths.

NIST has historically used electrically calibrated laser calorimeters to provide traceability to the SI units for laser power and energy. We recently developed a new measurement capability based on a Laser Optimized Cryogenic Radiometer (LOCR), which provides an order of magnitude improvement in accuracy for laser power measurements. To meet the increasingly demanding needs of higher accuracy over a larger range of optical power and wavelength, we find it necessary to improve the accuracy of calibration services through the development of better transfer standards traceable to LOCR.

MILESTONE: By 2002, reduce the uncertainties for all laser energy and power calibrations supplied to customers by at least a factor of 2. This will be accomplished through the development of improved laser power transfer standards with a greater range in optical power and wavelength.

The explosion of the rate of 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 DOD has begun to accelerate the use 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 the needs of these demanding customers.

MILESTONE: By 2001, reduce the uncertainties for optical fiber power calibrations supplied to customers by another factor of 2. This will be accomplished through the development of higher accuracy transfer standards and instrumentation to characterize these devices and accurately assess uncertainty budgets.



This articulated robot arm is used to characterize the "field-of-view" of a potential optical fiber power detector design. This measurement is critical as the light emerging from an optical fiber rapidly diverges, and the transfer standard must collect all of this light.

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 solid-state laser technology to keep up with customer needs for calibration services at NIST.

MILESTONE: By 2003, develop a tunable solid-state laser system 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.

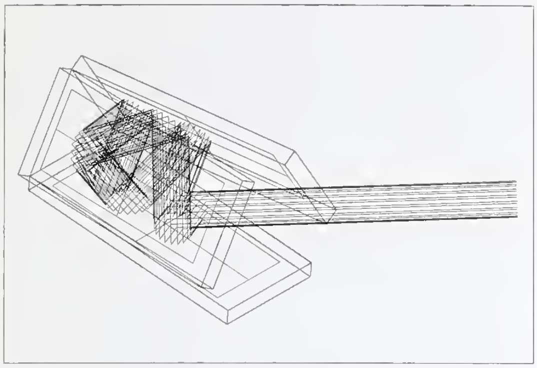
With the rapid development of wavelength division multiplexing (WDM) technology for optical fiber communications, the range of available diode laser wavelengths has increased dramatically. Calibration services at NIST will be required by the communications industry to support this new technology. Currently NIST uses a lamp/monochromator-based system to fill in the gaps in the wavelength coverage for optical fiber power meter calibrations, but this system is not optimum for providing high-accuracy optical fiber power meter calibrations. Research in diode laser technology using multiple quantum well structures (MQW) has demonstrated tuning ranges of greater than 100 nm. To meet the increasing demands for higher accuracy and wider wavelength coverage, NIST needs to implement these advances in tunable diode laser systems for calibration services applications.

MILESTONE: By 2002, develop tunable diode lasers based on MQW technology with very large tuning ranges for optical fiber power meter calibrations.

Accomplishments

- We improved accuracy of fiber optic power meter calibrations by a factor of two, completed a DOD funded project to improve fiber optic power meter calibrations in a high accuracy laser-optimized cryogenic radiometer (LOCR) to reduce the uncertainty of calibration services from 1 % to 0.5 %. Improved accuracy for the NIST calibrations will enable higher accuracy for end user equipment, and will result in tighter tolerances in optical fiber communication systems. DOD is investing heavily in fiber optic systems in many applications such as electromagnetic pulse (EMP) resistance, weight reduction, and high-speed communications.
- We completed documentation for optical fiber power meter calibration and linearity characterization services.
- We improved radiometer relevance. We developed an improved radiometer for optical measurements by using domain-engineered pyroelectric detector elements. We reduced their susceptibility to environmental acoustic noise and vibration, resulting in lower noise floor for optical measurements in most applications (collaboration with Division 844). This improves the general performance of pyroelectric detectors in optical measurements at NIST and other optical metrology labs.
- We built an automated system for 1 kW detector linearity measurements that uses a custom built reflective chopper wheel as a high power laser beam attenuator.
- We upgraded and refurbished the Air Force's MJ laser calorimeters. The calorimeters were designed and built by NIST

more than 25 years ago to support the DOD's high-energy laser programs.



An optical raytracing for a laser detector that uses multiple reflections off its inner surface to totally absorb the incident laser beam, converting the laser power to heat energy in the structure. Thermal sensors mounted on the device measure the increase in temperature.

FY Deliverables

Calibrations

101 tests performed on 72 items, with $145,845 income (October 1, 1999 to September 30, 2000)

Equipment Supplied to Other Agencies and National Laboratories:

- Special high sensitivity pyroelectric detectors with high spatial uniformity supplied to the NPL (National Laboratory of Great Britain) and the NMH (Hungarian National Laboratory).

- Domain engineered pyroelectric detectors supplied to Optical Technology Division in the Physics Laboratory and Raytheon.

- Various transfer standards for laser and optical fiber power delivered to DOD sponsors.

Standards Committee Participation

American National Standards Institute/Z136: Thomas R. Scott and John H. Lehman are members of this committee, which deals with laser safety.

International Organization for Standardization/ TC172/SC.09: Thomas R. Scott is a member and US delegation leader of this committee, which deals with Electrooptical Systems.

Optics and Electro-Optics Standards Council (OEOSC): Thomas R. Scott is a member of this committee, which deals with IEEE-LEOS.

U.S. National Committee of the International Electrotechnical Commission/TC076: John Lehman is a member of this committee which deals with Laser Equipment.

Telecommunications Industry Association/ FO06/SC.01/WG.10: Igor Vayshenker is a member of this working group, which deals with Metrology and Calibration.

Publications

"Optical Fiber Power Meter Nonlinearity Calibrations at NIST," I. Vayshenker, S. Yang, X. Li, T. R. Scott, and C. L. Cromer, NIST SP 250-56, 29 pp (Aug 00).

"NIST Measurement Services: Optical Fiber Power Meter Calibrations at NIST," I. Vayshenker, X. Li, D. J. Livigni, T. R. Scott, and C. L. Cromer, NIST SP 250-54, 36 pp (Jun 00).

"NIST Measurement Services: Optical Fiber Power Meter Nonlinearity Calibrations at NIST," I. Vayshenker, S. Yang, X. Li, T. R. Scott, and C. L. Cromer, NIST SP 250-56, 29 pp (Aug 00).

"Optical Fiber Power Measurements," I. Vayshenker, X. Li, D. J. Livigni, T. R. Scott, Proc., Meas. Sci. Conf. 2000, Anaheim, CA, Jan 19-21, 2000, CD-ROM, e-Doc Publish, Inc. (Jan 00).

Pulsed-Laser Radiometry

Technical Contact:
Marla L. Dowell

Staff-Years:
3.5 professionals
1.0 guest researchers

Funding Sources:
NIST (61 %)
Other Government Agencies (35 %)
Calibration fees (4 %)

Parent Program:
Optoelectronics

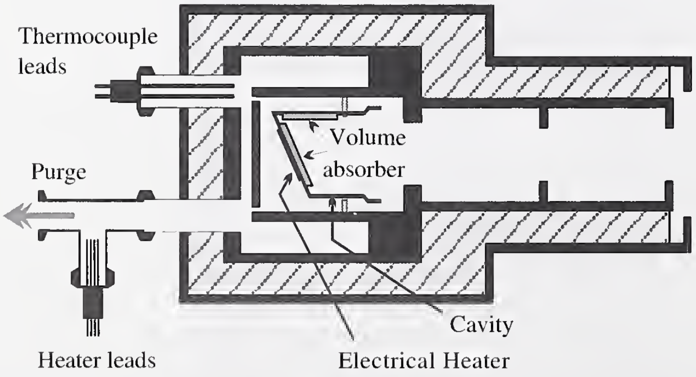
Project Goals

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 is 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 standards development, calibration services, and advising customers on in-house measurements. The bulk of our work is concentrated on ultraviolet (UV) laser metrology using excimer lasers.

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



Excicmer laser calorimeter for 193nm

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, the National Institute of Standards and Technology, with SEMATECH support, has developed primary standard calorimeters for both 193 nm and 248 nm excimer laser power and energy measurements.

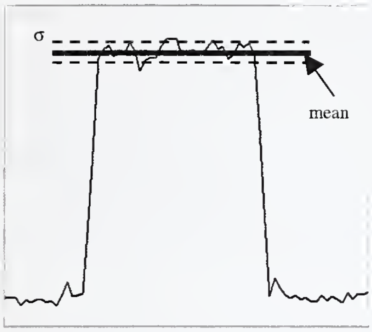
Technical Strategy

Beginning with the first edition of the National Technology Roadmap for Semiconductors in 1992, the semiconductor industry became more organized in its efforts 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, deep ultraviolet lasers, specifically KrF (248-nm) and ArF (193-nm), and more recently F2 (157-nm) excimer lasers, are the preferred sources for high-resolution lithography at this time. To meet the laser metrology needs of the optical lithography community, the NIST Optoelectronics Division has developed primary standards and associated measurement systems at 193 and 248-nm, and is in the process of developing standards for measurements at 157nm.

MILESTONE: By 2002, develop a 157 nm excimer laser primary standard and calibration service to provide support for the next generation of optical lithography.

In addition to existing DUV laser measurement services, there is increasing demand for laser dose, *i.e.*, energy density, measurements, where the detector samples a fraction of the total laser beam. Accurate laser dose measurements are important because small area detectors are widely used to monitor laser pulse energy density at the wafer plane of a lithographic tool. Accurate measurements of laser dose are especially crucial to the development of new mask resist materials, since lower dose requirements lead to greater wafer throughput as well as extend the lifetime of an exposure tool's optical components.

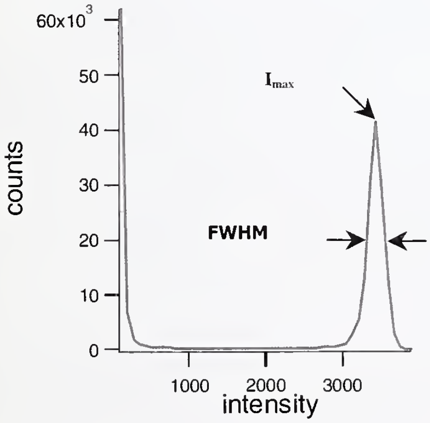
MILESTONE: By 2001, develop the capability at NIST of calibration services for energy density (dose) meters at 248 nm and 193 nm.



ISO 13694 definition of beam uniformity is σ/mean.

Excimer lasers are seeing increased use in the micromachining of small structures, such as inkjet nozzles and optical waveguides. Laser beam characterization measurements are critical in some of these processes since excimer laser beams are astigmatic.

MILESTONE: By 2001, develop capabilities at NIST for laser beam characterization and homogenization.



ISO 13694 definition of plateau uniformity is FWH M/I_{max}

Accomplishments

- **193 nm excimer laser power and energy meter calibration services.** With funding support from SEMATECH, we completed development of a new DUV primary standard calorimeter for measurement of 193 nm excimer laser pulse energy. We established a new service to calibrate customer power and energy meters for 193 nm excimer lasers with an uncertainty of ~ 1 %. (Collaboration with NIST Division 844 and MIT Lincoln Laboratory).

Significance: Standards traceable to SI units for DUV excimer laser pulse energy are important for medical applications such as excimer laser eye surgery, and for the semiconductor industry for accurate process control in computer chip manufacture.

- **DUV excimer laser transmittance of optical materials.** We developed a measurement system for the transmittance of optical materials (e.g., fused silica and calcium fluoride) using a 193 nm excimer laser. Measurements are performed in a nitrogen gas environment with an uncertainty of < 1 %, and are available to customers as a special test service. (Collaboration with NIST Division 844 and MIT Lincoln Laboratory).

Significance: Applications for 193 nm excimer lasers require accurate transmittance measurements of system components to assure performance and to meet design tolerances. Industry measurements of transmittance using both excimer lasers and traditional spectrophotometers show considerable disagreements (~ 5 %).

FY Deliverables

Calibrations

26 calibrations performed on 18 items.

Publications

"New Developments in Deep Ultraviolet Laser Metrology for Photolithography," M.L. Dowell, C.L. Cromer, R.W. Leonhardt, T.R. Scott; Proc., 2000 Int'l Conf. on Characterization and Metrology for ULSI Tech. (in press)

"New Developments in Deep Ultraviolet Laser Metrology for Photolithography," M.L. Dowell, C.L. Cromer, R.W. Leonhardt, T.R. Scott; Society of Manufacturing Engineers Technical Note (in press).

Technical Contact:
Paul D. Hale

Staff-Years:
4.0 professionals
0.5 technician
1.0 contractor
1.0 student

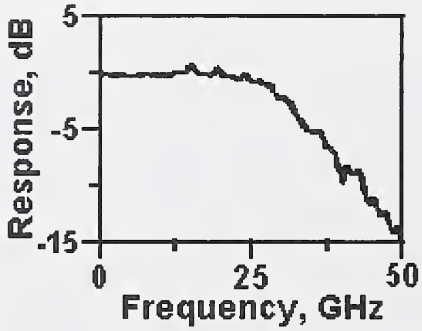
Funding Sources:
NIST (73 %)
Other Government Agencies (25 %)
Calibration Fees (2 %)

Parent Program:
Optoelectronics

High-Speed Measurements

Project Goals

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



Frequency response of optical communications receiver, obtained with swept-frequency heterodyne measurement system.

Customer Needs

High-bandwidth measurements are needed to support high-performance systems that take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second by use of pure time division multiplexing (TDM). Research is being done on the next generation of TDM systems at 40 to 80 gigabits per second in laboratories around the world. Methods are needed to characterize the scalar and vector frequency response of high-speed sources and detectors to at least the third harmonic of 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 frequency response measurements with low uncertainty.

Source and detector noise measurements are required to predict low bit error rates in computer interconnects, high carrier-to-noise ratios in analog systems, and to support erbium-doped fiber amplifier noise figure measurements.

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

Technical Strategy

NIST has developed highly accurate heterodyne techniques at 1319 nm for measuring detector frequency response and is extending this capability to 850 nm and 1550 nm. High-speed optoelectronic system design requires measurement of the phase response of optoelectronic components. Researchers in the High-Speed Measurements Project are developing time-domain techniques for measuring optoelectronic phase response with verifiable accuracy.

NIST is developing optical noise measurement systems for calibrating relative intensity noise (RIN).

NIST has developed methods for calibrating absolute laser pulse energy and peak power which are traceable to national cw laser power and energy standards maintained by the Sources and Detectors Group.

MILESTONE: By 2002, calibration service available for optoelectronic phase at 1550 nm.

The vector optoelectronic frequency response of a photoreceiver determines its impulse response. At present there are no accepted methods for measuring optoelectronic vector frequency response.

MILESTONE: By 2002, have certified optical noise sources available for calibrating optical amplifier noise figure.

Measurements of laser and optical amplifier noise commonly use a RIN subtraction or other techniques that will be investigated.

MILESTONE: By 2001, have calibration service available for 1550 nm low-level peak pulse power and pulse energy.

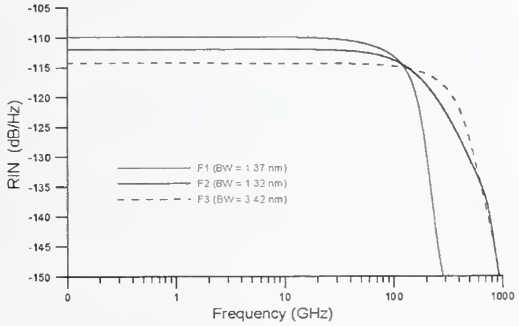
Pulse power and energy measurements are required for a new generation of eye-safe laser target designators and range finders.

MILESTONE: By 2001, have calibration service available for 850 nm optoelectronic scalar frequency response.

The recent explosion of high-speed interconnect applications that use multimode fiber and laser sources in the 750 nm to 850 nm wavelength region has greatly increased the need for test equipment for these systems. This includes reference receivers with well-characterized frequency response between about 1 MHz and 10 GHz. Since 10 gigabits per second systems are being considered for applications by several companies, and since components may need to be characterized to three times the bit rate, future needs may extend above 30 GHz.

Accomplishments

- A detailed uncertainty analysis of a 1319 nm heterodyne scalar frequency response measurement system was completed. This analysis was used as the foundation of a new calibration service for transfer standards, which is a fast photodiode combined with a RF power sensor. The combined stability of the heterodyne calibration system and a transfer standard was studied over one year.



RIN spectrum of three seperate sources calibrated from fundamental physical principles.

- A detailed uncertainty analysis of a RIN standard was completed. The standard consists of an erbium-doped fiber amplifier, narrow-band optical filter, and polarizer, and provides an amount of noise that can be calculated from first principles. This work provides the foundation of a Measurement Assurance Program for RIN.
- As part of the program to measure optoelectronic vector frequency response, a multidisciplinary collaboration between the Optoelectronics, Radio Frequency Technology, Statistical Engineering, and Electricity Divisions built the necessary procedures and algorithms to perform nose-to-nose calibration of high-speed digital sampling oscilloscopes. The procedures include time-base distortion measurement and correction, drift measurement and correction, signal alignment, mismatch correction, and nose-to-nose deconvolution. The procedures have also been applied to time-domain measurements of the frequency response of high-speed photoreceivers.

A new collaboration with the RF-Technology Division, through the EEEL sabbatical program, has given a preliminary demonstration of the use of time-domain electro-optic sampling combined with standard frequency-domain network analysis tools to measure the vector frequency response of a photoreceiver with low systematic error.

FY Deliverables

Calibrations

Ten calibrations performed on 10 items for 7 customers.

Standards Committee Participation

Telecommunication Industry Association/ FO02/SC.01/WG.01: Gregory Obarski is a member of this working group, which deals with Optical Amplifiers.

Telecommunication Industry Association/ FO06/SC.01/WG.10: Gregory Obarski and Paul Hale are members of this working group, which deals with Metrology and Calibration.

Publications

“Heterodyne System at 850 nm for Measuring Photoreceiver Frequency Response”; Hale, P.D.; Wang, C.-M., Tech. Dig., Symp. on Optical Fiber Meas., in NIST SP 953, 117-120; Sep 00

“Time-Domain Measurement of the Frequency Response of High-Speed Photoreceivers to 50 GHz”; Clement, T.S.; Hale, P.D.; Coakley, K.C.; Wang, C.-M. Tech. Dig., Symp. on Optical Fiber Meas., in NIST SP 953, 121-124; Sep 00

“Analysis of Interconnection Networks and Mismatch in the Nose-to-Nose Calibration”; DeGroot, D.C.; Hale, P.D. Conf. Dig., 55th Automatic RF Techniques Group, Going Beyond S-Parameters, Jun 15-16, 2000, IEEE MTT-S IMS2000, Boston, MA, 116-121; Jun 00

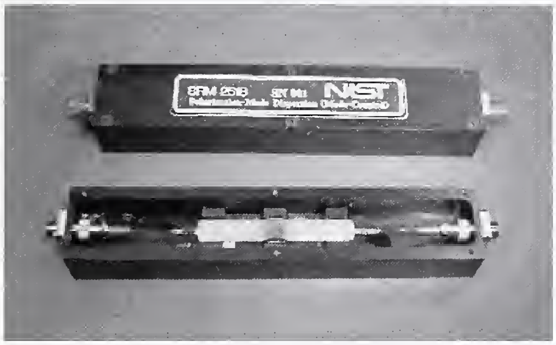
“Estimating the Magnitude and Phase Response of a 50 GHz Sampling Oscilloscope Using the "Nose-to-Nose" Method”; Hale, P.D.; Clement, T.S.; Coakley, K.J.;

Wang, C.-M.; DeGroot, D.C.; Verdoni, A.P.,Conf. Dig., 55th Automatic RF Techniques Group, Going Beyond S-Parameters, Jun 15-16, 2000, IEEE MTT-S IMS2000, Boston, MA: 116-121; Jun 00

Optical Fiber Metrology

Project Goals

Provide measurements, standards, and expertise to support fiber optic characterization for the optical telecommunications industry.



Polarization-mode dispersion (mode coupled) artifact (SRM 2518).

Customer Needs

The mature fiber optic market faces continuing metrology challenges imposed by demands for higher overall data transmission rates. Increased time-domain data rates push the need for characterization of fiber's dispersive properties; wavelength division multiplexing implementations require continuing improvements in measurements of spectral and nonlinear properties.

Technical Strategy

Chromatic dispersion in fibers is still an issue, and with higher data rates and larger portions of the optical spectrum in use, characterization needs for fiber chromatic dispersion are strong. The needs are changing from measurement of zero-dispersion wavelength to absolute dispersion in dispersion compensating modules, non-zero dispersion-shifted fiber, etc. This year, we plan to improve the stability of our fiber dispersion test system, document its test procedure to facilitate special tests of customer-supplied fibers, and perform specialty measurements for customers as appropriate.

MILESTONE: By 2001, fiber dispersion system modifications complete and test procedure documented for easy implementation on customer tests.

Polarization-mode dispersion (PMD) metrology remains a critical issue for optical telecommunications. We will produce more SRMs for mode-coupled PMD and release an SRM for non-mode-coupled PMD. We will continue performing special test measurements on customer-supplied artifacts and will document the PMD measurement system for this purpose. We will study new techniques (such as modulation-phase-shift) for narrow-band measurement of PMD.

MILESTONE: By 2001 SRMs 2518 and 2538 delivered and non-mode-coupled special test procedures documented.

Continued industry demand for fiber geometry artifacts requires us to produce more of SRM 2520 (fiber cladding diameter).

MILESTONE: By 2001, SRM 2520 delivered.

Accomplishments

- We completed certification and delivery of mode-field diameter artifacts (SRM 2513) characterized to 30 nm uncertainty, available for purchase.

- We conducted a round robin measurement comparison for industry participants on fiber nonlinear coefficient, multimode fiber laser launch and multimode fiber/source distribution validation.

- We summarized a few years work on multimode fiber launch-related performance through writing of Technical Service Bulletin document for the Telecommunications Industry Association.

- We performed special test measurements of chromatic dispersion on customer-supplied fibers.

- We delivered first batch of SRM 2518 (Polarization-mode dispersion – mode coupled) artifact (which sold out right away).

- We performed special test PMD measurements on customer-supplied artifacts (both mode-coupled and non-mode-coupled).

- We studied non-destructive technique of chromatic dispersion mapping along the fiber length using RF optical time domain reflectometry.

Technical Contact:
Paul A. Williams

Staff-Years:
3 professionals
0.5 guest scientists
0.5 Contractors

Funding Sources:
NIST base (80%)
NIST non-base (7 %)
Other Government Agencies (13 %)
Parent Program:
Optoelectronics

- We demonstrated spatially-resolved impulse response measurements on multimode fiber.

FY Deliverables

Calibrations/Special test measurements:

Chromatic dispersion: two customer-supplied dispersion-compensating modules measured for relative group delay and chromatic dispersion as a function of wavelength.

Polarization-mode dispersion: four customer artifacts measured for wavelength-averaged Differential Group Delay (both mode-coupled and non-mode-coupled).

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit *http://ts.nist.gov/srm* to obtain a catalog.

SRM 2513, Mode Field Diameter Standard for Single-Mode Fiber; available, 8 units sent to SRMP in FY 2000

SRM 2520, Optical Fiber Diameter Standard; available.

SRM 2522, Pin Gauge Standard for Optical Fiber Ferrules; available.

SRM 2523, Optical Fiber Ferrule Geometry Standard, in catalog.

SRM 2524, Optical Fiber Chromatic Dispersion Standard, no longer available.

SRM 2553, Optical Fiber Coating Diameter; available.

SRM 2554, Optical Fiber Coating Diameter; available.

SRM 2555, Optical Fiber Coating Diameter; available.

SRM 2518, Polarization-Mode Dispersion (Mode-Coupled), 7 units delivered in FY 2000, currently sold out.

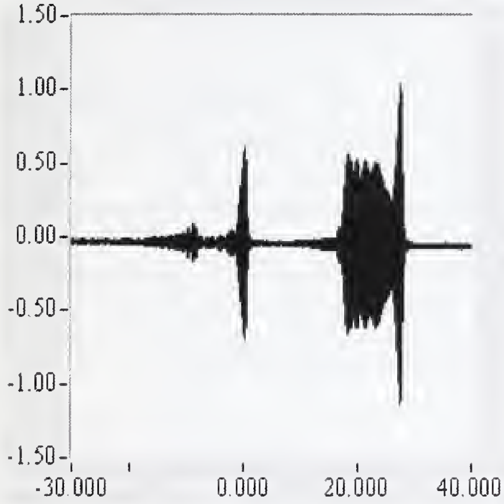
Publications

"NIST Artifact Standards for Fiber Optic Metrology"; Williams, P.A., Proc. Meas Proc., Meas. Sci. Conf. 2000, Anaheim, CA, Jan 19-21, 2000; CD-ROM, e-Doc Publish, Inc., Session IIB; Jan 00

Interferometry and Polarimetry

Project Goals

Develop interferometric and polarimetric metrology to support the optoelectronics industry and provide measurements and standards for industry and government laboratories.



Low coherence interferogram of two fiber Bragg gratings in a network of gratings.

Customer Needs

The rapid growth of high-bandwidth optical fiber communication systems has greatly increased the need for accurate measurement of fiber component spectral and dispersion properties. Chromatic dispersion is a very important issue for high bit rate systems; proposed systems will require dispersion measurement and control to unprecedented accuracy.

Polarization properties play a role in a variety of optical components and systems. Accurate measurement techniques and standards are needed to calibrate instruments that measure retardance, diattenuation, and depolarization.
Optical fiber sensors bring to metrology the same advantages that optical fibers provide to communications. Important advantages include immunity from electromagnetic interference and ease of multiplexing numerous sensors onto a single fiber. As optical fiber sensors are applied to critical applications such as structural monitoring and power generation, the lack of standards and calibrations is becoming evident. Standards are required to ensure the accuracy of systems during typical day-to-day usage as well as assuring reliable measurements over extended times (for example, bridge strain monitoring over decades) that may exceed the lifetime of some measuring subsystems.

Technical Strategy

Using low-coherence interferometry the project has demonstrated measurement of optical path length, group delay, and dispersion in various components. This system can make dispersion measurements 100 times faster than conventional methods, and provides improved spectral resolution. Unlike conventional dispersion measurement systems, the low-coherence technique can be used to distinguish and measure the dispersion of multiple components in a system. This is important in telecommunications applications where several gratings are used in series as add/drop multiplexers or dispersion compensators.

MILESTONE: By 2001, develop and characterize next-generation low-coherence interferometer and extend dispersion measurements to additional components.

MILESTONE: By 2002, use low-coherence interferometry techniques to measure polarization mode dispersion in components.

To assess fiber communication and sensor industry measurement capabilities, the project conducted two round robin intercomparisons for the measurement of spectral reflectance and dispersion of fiber Bragg gratings. The project is currently measuring these properties in other wavelength filter components.

MILESTONE: By 2001, measure polarization dependent wavelength shift of optical components.

Fiber Bragg grating sensors are now used to monitor civil structures, optimize oil and gas extraction from wells, and measure strain in military platforms. Despite the extraordinary measurement conditions and monitoring lifetimes that are envisioned in these applications, few calibrations and standards exist. Strain calibration is especially challenging because interfacial mechanisms may not perfectly transfer strain from the target structure to the sensing fiber. Furthermore, direct calibration of sensors and systems in the field is currently limited by the

Technical Contact:
Paul A. Williams

Staff-Years:
3 professionals
0.4 technicians
1.25 post doc
1.0 PREP (grad)
1.0 PREP (undergrad)

Funding Sources:
NIST Base (69 %)
NIST other (15 %)
Other Government Agencies (16 %)

Parent Program:
Optoelectronics

accuracy of instrumentation available for testing.

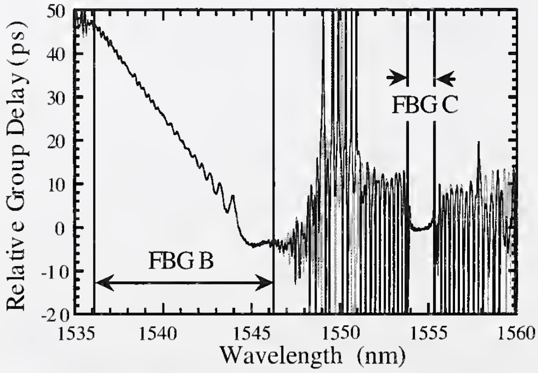
MILESTONE: By 2002, develop artifacts with well-characterized spectral reflectance and supporting metrology that can be used to improve the calibration of fiber Bragg grating demodulation/measurement units.

The project can measure linear retardance with better than 0.1° uncertainty and performs special tests at visible and near-infrared wavelengths. We are expanding our capabilities to include the measurement of other polarization parameters such as diattenuation, circular retardance, and depolarization.

MILESTONE: By 2001, characterize Muller matrix diattenuation and depolarization measurements.

Accomplishments

- We demonstrated the measurement of individual fiber Bragg grating (FBG) dispersion in a single measurement of a network of 3 FBGs. Grating signatures were isolated from a single interferogram in the temporal domain and processed individually to obtain dispersion. Dispersion of the entire network can also be obtained simultaneously in the spectral domain after eliminating a beating term due to FBG proximity. The simultaneous measurement of multiple gratings is important in telecommunications applications where several gratings are used in series as add/drop multiplexers, and in cases where several gratings are concatenated to achieve desired dispersion characteristics.

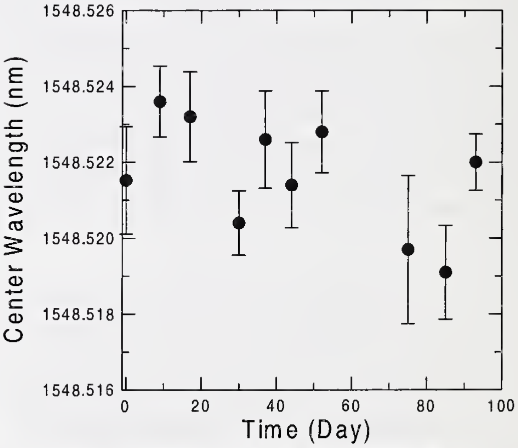


Relative group delay of two fiber Bragg gratings measured simultaneously.

- We have measured the relative group delay of a hydrogen cyanide molecular absorption line using low-coherence interferometry. This measurement demonstrates the ability of the low-coherence interferometer to measure the relative group delay of spectrally narrow features in fiber-optic components. We are evaluating the molecular absorption line as a potential dispersion calibration reference.

- We completed two round robins of fiber Bragg grating spectral reflectance and dispersion measurements involving 12 participants. We completed the round robin data analysis and presented the results at the January Telecommunications Industry Association meeting and the Optical Fiber Communication Conference in March. The round robins showed that there is a great need for definitions and standard measurement procedures for properties such as bandwidth, center wavelength, and dispersion.

- We have evaluated thin film and Bragg grating based fiber components for a passive artifact that will provide a way to calibrate fiber Bragg grating sensor systems. The best component measured so far is an athermally packaged fiber Bragg grating. The grating's center wavelength shows a standard deviation of 1.5 pm over 93 days.



Center wavelength drift of an athermally packaged fiber Bragg grating.

- We have completed measurements of the temperature dependence of birefringence in MgF_2 and SiO_2 at 633, 787, 1318, and 1535 nm.

- We demonstrated a novel system for simultaneously measuring optical disc in-plane and vertical birefringence. In contrast to traditional methods that obtain these values from many measurements made over a range of incidence angles, this system makes a single measurement at a spot illuminated by a focused beam. The birefringence values obtained from both methods agree to within 5 %. This new method has the potential for rapid, non-destructive measurements in a system compatible with present disc tester designs.

FY Deliverables

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit *http://ts.nist.gov/srm* to obtain a catalog.

SRM 2525, Optical Linear Retarder, available.

Collaborations

Collaboration with NxtPhase (Phoenix, AZ) on annealed fiber current sensors.

External Recognition

Allen Rose was named an Associate Editor of the journal IEEE Photonics Technology Letters

Publications

"A Fast and Accurate Measurement of Both Transmission and Reflection Group Delay in Fiber Bragg Gratings"; Dyer, S.D.; Rochford, K.B. Tech. Dig., Symp. on Optical Fiber Meas., in NIST SP 953, 1;69-172; Sep 00

"Fiber Bragg Grating Metrology Round Robin": Telecom Group; Rose, A.H.; Wang, C.-M.; Dyer, S.D. Tech. Dig., Symp. on Optical Fiber Meas., in NIST SP 953, 161-164; Sep 00

"Annealing Optical Fiber: Applications and Properties"; Rose, A.H. Am. Ceram. Soc. Bull. 79(3): 40-43; Mar 00

Technical Contact:
Sarah L. Gilbert

Staff-Years:
2.75 professionals
0.4 technicians
1 post doc

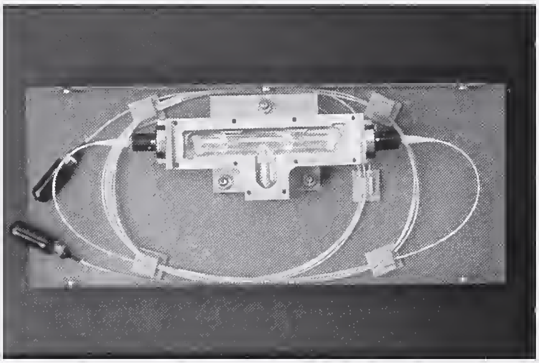
Funding Sources:
NIST Base (43 %)
NIST Non-base (31 %)
Other Government Agencies (26 %)

Parent Program:
Optoelectronics

Fiber and Discrete Components

Project Goals

Develop measurement methods for characterization of optical fiber and discrete components and develop calibration standards needed by industry to calibrate optical fiber test equipment.



SRM 2519 wavelength calibration reference.

Customer Needs

The project is concentrating on the needs of the optical fiber communications industry, particularly optical component metrology and wavelength calibration for wavelength division multiplexed (WDM) systems. In a WDM system, bandwidth is increased by sending many channels with different wavelengths down a single optical fiber. WDM systems use a variety of optical components and new components are under development for next-generation systems. Future systems will likely use narrower channel spacing and a broader wavelength region. For effective system operation, the wavelength and polarization dependence of WDM optical components must be characterized and controlled. Also, the ability of channel filters (multiplexers, demultiplexers, and drop/add filters) to separate channels and minimize crosstalk is a critical factor.

Technical Strategy

Supporting WDM component metrology needs requires developing and evaluating new measurement techniques, disseminating this knowledge, and, when appropriate, developing Standard Reference Materials to help industry calibrate instrumentation. The project currently focuses on two areas: (1) wavelength standards for WDM, and (2) polarization-dependent loss and wavelength shift metrology.

Wavelength standards are needed to calibrate instruments that measure the wavelengths of sources and characterize the wavelength dependence of WDM components. The project currently produces two wavelength reference Standard Reference Materials: SRM 2517a (acetylene, high resolution) and SRM 2519 (hydrogen cyanide) that can be used to calibrate the wavelength scale of instruments between 1510 and 1565 nm. WDM will soon expand into other wavelength regions, such as the 1565-1625 nm L band and the 1300-1500 nm region.

MILESTONE: By 2001, provide a wavelength reference SRM for the WDM L band and complete the development of a high accuracy reference for the 1300 nm region.

MILESTONE: By 2002, develop references for the 1300-1500 nm region.

Polarization-dependent loss (PDL) of components and polarization-dependent wavelength shift (PDW) of WDM channel filters must meet increasingly more stringent requirements as the systems become more complex and the channel spacing decreases. The project has developed an accurate PDL measurement system and is now extending this capability to measure PDL wavelength dependence and PDW. In addition, a new SRM is under development to help industry calibrate their PDL measurement instrumentation.

MILESTONE: By 2001, provide a PDL SRM and develop a high resolution PDL and PDW measurement system.

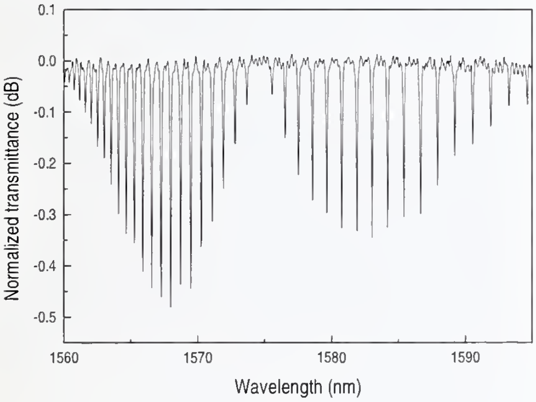
MILESTONE: By 2002 extend measurement capability to other WDM regions.

Accomplishments

- We completed the development of a high-resolution acetylene wavelength reference Standard Reference Material, SRM 2517a, and the SRM has been approved by the EEEL MCOM review committee. Fifteen absorption lines are certified with an uncertainty of 0.1 pm, 2 lines are certified with an uncertainty of 0.6 pm, and the remainder of the lines are certified with an uncertainty of 0.3 pm. This SRM replaces SRM 2517 and can be used in applications requiring higher resolution and higher accuracy.

- We have stabilized a diode laser to a methane absorption line and have measured the absolute frequency of this source by comparing it with a calcium frequency standard developed by the NIST Time and Frequency Division. This resulted in the measurement of the frequency of a methane transition at 1314 nm with an uncertainty of less than 5 MHz. This methane-stabilized laser now serves as a NIST internal calibration reference.

- We investigated wavelength references for the WDM L band region (approximately 1565-1630 nm) and have selected carbon monoxide. We have completed the preliminary design of the SRM, have constructed a prototype, and have begun measuring the pressure shift of the absorption lines.



Carbon monoxide ($^{12}C^{16}O$) spectrum.

- We constructed a prototype hybrid wavelength reference device. The device, which uses multiple superimposed fiber Bragg gratings and an absorption cell, can provide wavelength calibration capability for spectral regions where there are no reasonable molecular or atomic wavelength references. We have studied the polarization dependence of the hybrid reference and find that the polarization sensitivity varies, depending on the fiber type.

- We have conducted an uncertainty analysis of our wavelength-selective PDL measurement system and have completed the development of a PDL artifact reference. This reference will become a NIST Standard Reference Material with a nominal PDL of 0.1 dB.

FY Deliverables

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit *http://ts.nist.gov/srm* to obtain a catalog.

SRM 2517, Wavelength Reference Absorption Cell – Acetylene $^{12}C_2H_2$; available, 10 units delivered in FY 2000.

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

SRM 2519, Wavelength Reference Absorption Cell – Hydrogen Cyanide ($H^{13}C^{14}N$); available, 33 units delivered in FY 2000.

Collaborations

Collaboration with the NIST Time and Frequency Division to conduct high-accuracy measurements of absorption lines in the 1300 nm region.

Publications

"Accurate spectral characterization of polarization dependent loss," R.M. Craig, in Technical Digest: Symposium on Optical Fiber Measurements, 2000, NIST Spec. Pub. 953, pp. 113-116 (Sep 2000).

"Pressure-induced shift and broadening of 1510-1540 nm acetylene wavelength calibration lines," W.C. Swann and S.L. Gilbert, J. Opt. Soc. Am. B **17**, pp.1263-1270 (Jul 2000).

"Wavelength calibration standards for wavelength division multiplexing," S.L. Gilbert and W.C. Swann, in Proc., 1999 Optical Fibre Meas. Conf., Nantes, France, (Oct 1999).

Technical Contact:
Norman A. Sanford

Staff Years:
2.1 professionals

Funding sources
NIST base (54 %)
NIST non-base (46 %)

Parent Program:
Optoelectronics

Optical Materials Metrology

Project Goals

Develop complementary metrology methods of nonlinear optical analysis, X-ray diffraction imaging, and cathodoluminescence for studies of optical, electronic, and structural features of bulk and thin film group-III-nitrides. Develop modeling, fabrication, and metrology methods for photonic crystals and single photon turnstile devices. Maintain established nonlinear optical analysis techniques for the uniformity analysis of $LiNbO_3$ in support of device manufacturers of high-speed modulator devices for optical telecommunications.

Nonlinear optical measurement system for nondestructive mapping of composition, strain, refractive index, and thickness in materials including lithium niobate and the group III-nitrides.

Customer Needs

Customer needs fall into two main categories: (1) development of metrology suites for rapid non-destructive uniformity characterization of photonic materials in terms of optical, electronic, and structural characteristics for bulk crystals and thin films, (2) development of new competence in the areas of photonic crystals, spontaneous emission control of quantum dots, and single photon turnstile devices.

The success of our previous work in the nonlinear optical characterization of $LiNbO_3$ has led in a very natural way to extending this work into other important photonic materials such as the group-III-nitrides. GaN has made enormous recent economic impact with the realization of semiconductor lasers and LEDs emitting in the blue. Other important applications of this material include high-power, high-temperature transistors and solar-blind UV detectors. In frustration to these application demands, however, problems with bulk and thin film growth of these materials remain, and thus the importance of developing new metrology methods is crucial. 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. AlGaAs is a well-established and important material; nevertheless there are increasing industry demands for more precise and reliable *in situ* and *ex situ* metrology methods.

$LiNbO_3$ is the material of choice for the fabrication of high-speed (~40 GHz) optical modulators. These devices are in increasing demand for the rapid global expansion of wavelength-division-multiplexed optical telecommunication systems. Notably, in 1999 the installation rate of 10 GHz fiber optic communication systems increased to approximately 8,000 per year, and all of these systems required $LiNbO_3$ modulators. Higher speed 40 GHz systems are expected to impact the market in a few years. Accordingly, NIST receives numerous requests for $LiNbO_3$ evaluation services.

Finally, the new areas of photonic crystals, spontaneous emission control of quantum-confined structures, and single photon turnstile devices are opening up exciting opportunities to meet needs in quantum-based radiometric measurements, quantum cryptography, quantum optics, quantum computing, and new architectures for optical telecommunications.

Technical Strategy

Nonlinear optics (NLO) offers rapid and versatile measurement capabilities that may be used to examine bulk and thin film materials at various stages of crystal growth and device processing. Furthermore, NLO methods may be directly correlated to other conventional measurement methods. Thus, material uniformity evaluated using NLO methods may, in many cases, be directly related to the material information derived from analytical methods that are not conveniently adapted to the manufacturing environment. For example, our strategy in applying nonlinear optical analysis methods to the study of bulk GaN single crystals relies on correlating the NLO results with X-ray diffraction imaging performed at Brookhaven National Laboratory in collaboration with NIST's Materials Science and Engineering Laboratory (MSEL). NLO is extremely sensitive to such undesirable structural features such as stacking faults, domain reversals, and mixed cubic and hexagonal phases. X-ray diffraction imaging reveals full-crystal images of stacking faults and domain reversals, but is less sensitive to the presence of mixed phases. Thus, a combination of NLO analysis and X-ray imaging methods results in a reduction in ambiguity compared to the case where only one method is employed. The NLO work grew out of our earlier work with the characterization of $LiNbO_3$ whereby we have developed methods for fully nondestructive evaluation of composition and strain in finished wafers of the material. Studying wafers cut sequentially from full boules has allowed us to track these quantities and relate them to growth conditions of large crystals. We anticipate similar evolution of the NLO work aimed at the group-III-nitrides. Furthermore, we are working toward correlating the results of the NLO investigations with new collaborations with NIST's MSEL involving cathodoluminescence studies of GaN, in addition to the high-resolution X-ray diffraction imaging studies.

MILESTONE: By 2001, establish wavelength tunable nonlinear optical characterization methods for thick film (thickness ranging from roughly 1μm to 100 μm) and bulk GaN and other III-nitride alloys.

MILESTONE: By 2001, correlate X-ray diffraction imaging data with NLO data on bulk GaN crystals.

MILESTONE: By 2001, establish wavelength tunable nonlinear optical characterization methods for thin III-nitride films (thickness ranging from roughly 5 nm to 100 nm).

MILESTONE: By 2002, conduct etching studies and correlate depth-dependent NLO analysis and cathodoluminescence analysis of structural features.

MILESTONE: By 2002, using NLO and linear optics, begin compiling database for optical constants of group-III-nitride alloys.

The research efforts surrounding photonic crystals and the single photon turnstile rely on advances in a number of key areas. Control and measurement of the size, shape, location and optical properties of nanostructures are fundamental. The modeling of photonic crystals will support the precision fabrication of these structures. Much work is also required for the accurate modeling of quantum dots, and the correlation with electrical and optical properties. The use of self-assembled InAs/GaAs quantum dots holds great promise for the near-room-temperature operation of photon turnstiles due to the strong Coulomb blockade effect observed. Development in the growth and electrical contact to single quantum dots, and the integration of quantum dots with single-electron pumps are being pursued toward this goal.

MILESTONE: By 2001, demonstrate optically pumped photon turnstile.

MILESTONE: By 2002, measure single photon turnstile operation with single electron pump.

MILESTONE: By 2002, establish design and fabrication methods for photonic crystals.

Microstructural characterization of materials is especially important to the development of rapidly growing technologies, such as those based on group-III nitrides or quantum dots. Here the emphasis on achieving record device performance often leaves behind the basic measurements needed to understand the long-term viability of the technologies. We are applying techniques based on atomic force microscopy and electron microscopy to study growth mechanisms, uniformity, surface morphology, and defect structure in these semiconductor materials. The measurements are correlated with optical and high-resolution X-ray measurements in a collaborative cross-division program.

MILESTONE: By 2001 characterize the density and size uniformity of InAs quantum dots as a function of growth conditions. Characterize the surface structure of etched gallium nitride.

Accomplishments

-Nonlinear optical analysis was used to examine the optical and structural properties of GaN bulk crystals grown by high-pressure processing, and thin films of the material grown by HVPE and MOCVD, and MBE. The results show distinct variations in both the index of refraction and the magnitude of the nonlinear optical coefficients from the bulk material to the MOCVD material. The wide variation in index and birefringence was seen to depend on the growth method and film thicknesses. For example, the results for bulk GaN plates (roughly 144 µm thick) reveal that the material is negative uniaxial with $n_e = 2.38$ and $n_o = 2.41$ at a wavelength of 532 nm. On the other hand, for GaN films (roughly 67 µm thick) grown by HVPE on sapphire substrates, the measured birefringence is positive with $n_e = 2.40$ and $n_o = 2.36$ at a wavelength of 532 nm. Both of these results agree well with the literature. Data for the thinner material (roughly 1-3 µm thick), grown by either MBE or MOCVD, produced ambiguous results. Perhaps the most important result revealed so far by the nonlinear optical analysis is evidence of stacking faults and mixed cubic/hexagonal phases. The existence of stacking faults and domain-inverted regions was corroborated in the bulk GaN samples, using high-resolution X-ray diffraction imaging in collaboration with NIST Materials Science and Engineering Laboratories researchers.

-In collaboration with other researchers of the Electronics and Electrical Engineering Laboratory, electrical contact to a single InGaAs quantum dot was demonstrated through the use of a Scanning Electron Microscope (SEM) and electron beam lithography. Suitable growth conditions were achieved to produce a sufficiently low density array of quantum dots. Dot density was approximately 10^9 cm^{-2}, dot widths were approximately 20 nm, and the contact width was 50 nm. The demonstration is an important step toward the measurement of capacitance of a single dot and the development of a single photon turnstile. A chemically assisted ion-beam etching system was designed, constructed, and operated to build competence in the fabrication of photonic crystal structures for this project.

-Atomic force microscopy (AFM) was used to characterize InGaAs quantum dots on GaAs as functions of temperature, As flux, growth rate and thickness. By varying these growth conditions, we have achieved control of the real dot density from about 5×10^8 cm^{-2} to about 5×10^{10} cm^{-2}. Dots grown at temperatures from 460 to 540 °C were imaged. The temperature range over which the growth was uniform was quite small (480 to 520 °C). The density of dots was found to be a linear function of temperature over this range. The development of new, more accurate and flexible software for AFM image analysis was initiated.

FY Deliverables

External Recognition

Sanford continues to serve as an Associate Editor of the IEEE Journal of Quantum Electronics. In this capacity, he is arranging for the publication of a Special Topics issue on photonic crystals, controlled spontaneous emission and related technologies.

Publications:

"Comparative Maker Fringe Analysis of Bulk and Thin Film GaN," N. A. Sanford, J. A. Aust, R. P. Mirin, J. Torvik, and J. I. Pankove," Materials Research Society Symposium Proceedings Series, Vol. 622, MRS Spring Meeting, April, 2000, San Francisco, CA, paper T5.9.

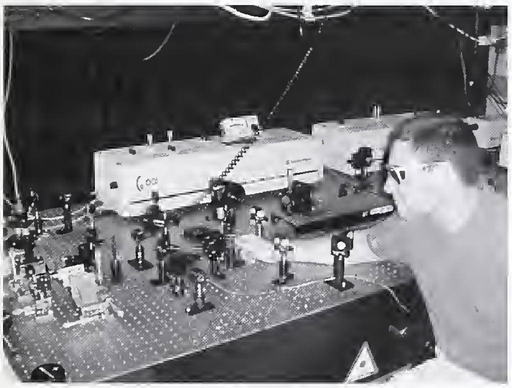
"Crystal Growth, Characterization, and Domain Studies in Lithium Niobate and Lithium Tantalate Ferroelectrics," V. Gopalan (Penn State University), N. A. Sanford and J. A. Aust (NIST, USA), K. Kitamura (NIRIM, Japan), in Handbook of Advanced Electronic and Photonic Materials and Devices, edited by H. S. Nalwa, Vol. 4: Ferroelectrics and Dielectrics, Academic Press (2001). (*invited*)

"Maker Fringe Analysis and Electric-Field Poling of Lithium Niobate," J. A. Aust, Ph.D. thesis, University of Colorado Dept. of Electrical Engineering, 1999.

Advanced Fabrication and Modeling

Project Goals

Develop advanced photonic modeling, fabrication and ultrafast measurement systems that support the improvement of manufacturing efficiency for optoelectronic devices. Fabricate specialty, solid-state waveguide lasers for use in metrology and other applications in NIST, industry, and other government laboratories.



Ultrafast measurement system with tunable wavelength for pump-probe characterization of compound semiconductor structures

Customer Needs

The Optoelectronics Industry Development Association (OIDA) has stated as strategically important the development of optoelectronic computer-aided-design tools. One difficulty for the construction of a suite of numerical tools for optoelectronics modeling is that the accuracy of existing numerical codes is typically not known. In many cases, existing tools are useful only for qualitative results. When several such modeling tools are to be integrated, there can be no assurance that even qualitative correctness will be achieved. There exists a need for model verification through standardized problem sets and precise measurement of relevant parameters.

Compact, solid-state waveguide lasers and amplifiers are emerging as a technology with impact ranging from telecommunications to high-speed signal processing to detector metrology. With assistance from corporate and DARPA 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 detector frequency response measurements or all-optical, analog-to-digital conversion applications.

As telecommunication systems move to higher transmission rates, measurement of the ultrafast properties of semiconductor structures used in those systems is becoming more important. In addition, the characterization of promising new devices continues to drive technology advances. These include quantum dot amplifiers having greatly reduced cross-gain modulation and semiconductor saturable absorbers for mode-locked lasers used in signal processing and THz wave generation.

Technical Strategy

Our approach to the characterization of optoelectronic components is three-pronged. It combines model development with focused device manufacture and measurement. Modeling can be used for both predictive design and experimental design for new measurement systems. We anticipate that the linking of modeling, manufacturing, and metrology efforts will be a benefit to all three by providing consistency checks.

In collaboration with the NIST Information Technology Laboratory, we are developing computer simulations for both active and passive components, including waveguide and fiber gratings, and waveguide lasers and amplifiers. We are demonstrating the accuracy of methods developed at NIST on problems with known solutions and comparing with other solutions obtained from modeling that are available commercially. We have developed two-dimensional, finite-element-method codes and are developing three-dimensional, finite-element, beam propagation method (BPM) algorithms that are suitable for solving wide-angle bi-directional BPM problems, anisotropic BPM problems, and problems with waveguides with axially varying refractive index profiles and defects. We are creating a Java user interface for all of our waveguide codes for public dissemination

Technical Contact:
Norman A. Sanford

Staff-Years:
1.7 professionals
1.0 graduate student

Funding Sources:
NIST base (52 %)
NIST non-base (9 %)
Other Agency (39 %)

Parent Program:
Optoelectronics

to enable use on any type of computer system. We will use a 3-D finite difference time-domain program to investigate the coupling of spontaneously emitted photons into resonant cavity modes of photonic crystals. This will support the development of photon turnstiles for high precision radiometry.

MILESTONE: By 2001, determine, through modeling, the appropriate material and device parameters for achieving stable, cw mode-locked operation of erbium/ytterbium-doped waveguide lasers.

MILESTONE: By 2002, model the properties of photonic crystals to assist the development of the single photon turnstile.

Compact glass waveguide lasers offer several advantages over their counterpart semiconductor diode lasers or fiber lasers. Solid state lasers are inherently able to demonstrate linewidths narrower than those of diode lasers, using much simpler manufacturing technology. They are also less susceptible to wavelength drift over their operating lifetimes, have higher optical damage thresholds, and have much better high-frequency noise figures than do semiconductor lasers. Compared to rare-earth-doped fibers, Yb/Er-doped glass waveguides can be engineered to result in significantly higher gain per unit length, enabling small, high-power, and easily packaged devices. NIST has pioneered the development of rare-earth-doped waveguide lasers in collaboration with industrial partners. The effort includes emission and absorption spectroscopy of the host glasses, optimization of the glass composition and ion-exchange process for maximum laser efficiency, development of distributed Bragg reflector (DBR) grating fabrication for applications requiring single frequency operation, and development of saturable Bragg absorbers for mode-locked laser operation.

MILESTONE: By 2001, characterize saturable and non-saturable losses of semiconductor saturable absorber mirrors.

MILESTONE: By 2002, demonstrate tunable DBR waveguide laser having 100 kHz linewidth.

MILESTONE: By 2002, demonstrate mode-locked, solid state waveguide laser operating at 10 GHz, with pulse-to-pulse timing jitter of less than 10 fs.

The project has established a test-bed for making ultrafast measurements in the 700 to 2300 nm wavelength range using a mode-locked Ti:Sapphire laser and optical parametric oscillator. This allows us to measure the carrier dynamics in structures such as semiconductor saturable absorbers and self-assembled quantum dots. It also enables nonlinear optical studies of important material systems, such as the group III nitrides, to determine index uniformity, defect structure and crystalline phase information. Quantum dot semiconductor optical amplifiers are predicted to have a greatly reduced cross-gain modulation and increased saturated gain compared to amplifiers with a quantum well or bulk gain medium. Fundamental optical studies of quantum dots are being pursued.

MILESTONE: By 2001, characterize the fluence and wavelength dependence of carrier decay times of semiconductor saturable absorbers.

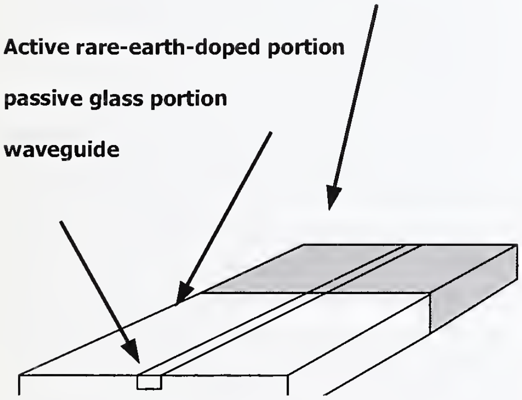
MILESTONE: By 2001, measure and model the bias-dependence and temperature-dependence of cross-gain modulation in InGaAs quantum-dot semiconductor optical amplifiers.

Accomplishments

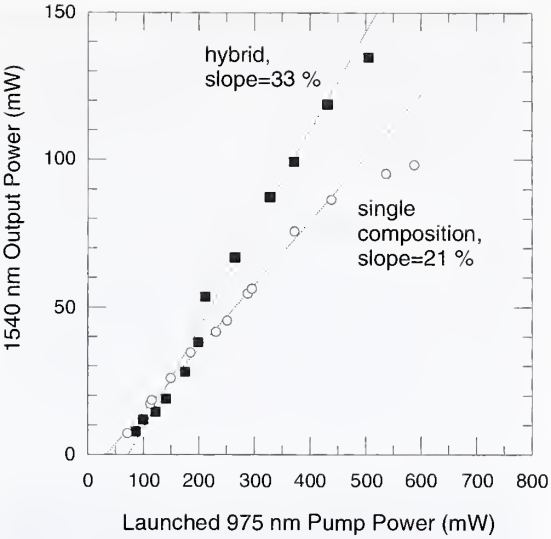
In collaboration with researchers at NIST's Information Technology Laboratory, we expanded the waveguide laser modeling code to simulate amplifier operation, enabling the optimization of Er and Yb doping concentration, device length, waveguide mode field size, and pump power. The model includes calculations of amplified spontaneous emission and the effects of cross-gain modulation. A three-dimensional beam propagation model was added to the finite element modeling code and tested. The software can handle a wide range of refractive index geometries. A new Java user interface was written to allow user-friendly setup and operation of the waveguide simulation codes. Post-processing capabilities permit the user to view contour plots of excited species and electric field.

- We grew semiconductor saturable absorber mirrors (SESAMs) and characterized them using a pump-probe system at 1540 nm that was designed and set up this year. The ultrashort (~100 fs) time constant due to carrier-carrier scattering indicated that self-starting of mode-locked laser operation will be possible, and the short time constant due to recombination could be made to vary from about 800 fs to about 3.5 ps, depending on the growth temperature. We procured and set up an advanced ultrafast measurement system including an optical parametric oscillator that allows expanded spectral response characterization.

- In collaboration with a CRADA partner, we demonstrated cw operation of a laser in a novel hybrid glass substrate composed of a rare-earth-doped segment thermally bonded to a passive segment. The joint is robust and allows waveguide fabrication on both sides with the identical ion-exchange process. A differential etch rate due to the ion-exchange was measured between the two segments. However, no change in surface quality was detected, and the efficiency of the hybrid laser was at least as high as that of an equivalent non-hybrid laser. The hybrid laser configuration will allow the optimization of laser cavities by permitting separate variation of the gain length and overall cavity length in the case of mode-locked lasers and separate placement of the gain and distributed Bragg reflector (DBR) regions in the case of single-frequency lasers.



Schematic of solid-state waveguide laser fabricated in a hybrid bonded-glass substrate. The substrate is composed of a passive glass section and a rare-earth-doped section containing both erbium and ytterbium.



Comparative operation of solid state waveguide lasers fabricated in a hybrid glass substrate and a uniformly rare-earth-doped substrate. The hybrid glass device displays improved performance.

- A series of DBR waveguide lasers in Yb/Er co-doped glass were fabricated and evaluated. All specimens had operating wavelengths falling within 0.1 nm of the 50 GHz ITU grid for wavelength division multiplexing, indicating a high uniformity of the grating fabrication process. We developed a waveguide burial process in the Yb/Er co-doped phosphate glass that will bring the optical mode away from the surface and consequently result in greater laser efficiency.

Deliverables

Publications

"Yb/Er-Codoped and Yb-Doped Waveguide Lasers in Phosphate Glass;" Veasey, D.L.; Funk, D.S.; Peters, P.M.; Sanford, N.A.; Obarski, G.E.; Fontaine, N.; Young, M.; Peskin, A.P.; Liu, W.-C.; Houde-Walter, S.N.; Hayden, J.S.; J. Non-Crystalline Solids, 263 & 264, 369-381; Mar 00

Technical Contact
Kris Bertness

Staff Years:
2.5 professionals
0.2 guest scientists
graduate students

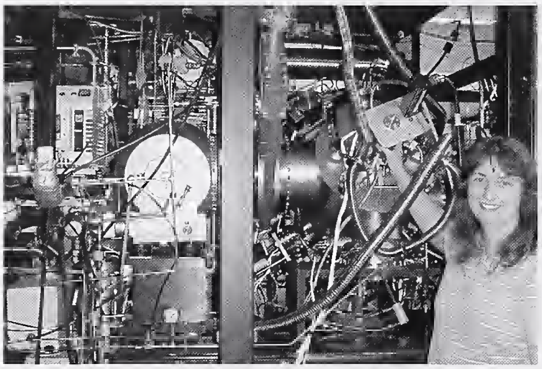
Funding Sources:
NIST base (60 %)
NIST non-base (23 %)
Other Agency/CRADAs (17 %)

Parent Program:
Optoelectronics

Semiconductor Growth and Devices Project

Project Goals

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



Gas-source molecular beam epitaxy system for III-V semiconductor growth and *in situ* monitoring research.

Customer Needs

The rapid growth of the U.S. optoelectronics industry is dependent on the high-yield manufacture of devices with increasingly tight specifications. Compound semiconductor materials form the basis for LEDs, lasers, photodetectors, and modulators critical to optical communication, display, data storage, and many other applications. Materials purity and uniformity issues are at the foundation of device yield and performance. Measurements of starting materials and epitaxial layers must be supported by standard procedures and reference materials. Increasingly the needs are for accurate in-process measurements. In addition, specialty devices are needed for use in metrology systems both within and outside of NIST.

Technical Strategy

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 short product cycle times. The problems have been exacerbated by the increase in outsourcing of epitaxial growth. 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 composition determination (photoluminescence (PL), photo-reflectance (PR), and X-ray diffraction (XRD)) with less common methods (*in situ* monitoring, electron microprobe analysis (EMPA), and quantitative chemical analysis) to enable certification of alloy composition. This program will pave the way for future production SRMs in the AlGaAs alloy system. As part of this research, we are quantifying error sources and accuracy limits of the indirect composition measurement techniques currently in use by industry, specifically PL and XRD. We are also demonstrating the composition accuracy that can be achieved with direct microanalysis techniques such as EMPA in combination with accurate reference artifacts and carefully chosen correction procedures.

MILESTONE: By 2002, develop AlGaAs composition standards with mole fraction uncertainty measured to ± 1 %.

In a related project, the accuracy of InGaAsP composition analysis is being assessed through an interlaboratory comparison of conventional *ex-situ* characterization techniques: PL, PR and XRD. This program seeks to develop reliable measurement and data analysis methods that can be used throughout the industry. A set of three samples with different compositions is being analyzed by industry, government and university laboratories. By examining the different operating conditions used in the various laboratories and how they affect the data, the importance of the measurement variables for the three techniques will be assessed. A necessary aspect of the study will be to distinguish between variations intrinsic to the materials and those caused by the measurement systems or techniques. In addition to the directly measured data, NIST will examine the materials parameters, such as composition and thickness, that the laboratories infer from their measurements.

Through repeated measurements and cross-correlation this work will help clarify appropriate measurement and calculation methods.

MILESTONE: By 2002, analyze important variables to control in ex-situ characterization of InGaAsP.

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 source material purity from vendor lot to vendor lot and as the vendors change process or packaging. The issue is described by industry as primarily a measurement problem in that manufacturers frequently report impurity levels as "not detected" for a series of lots that produce very different device results. The critical concentrations of the impurities are not well known; however, it is believed that >10 nmol/mol oxygen or water in phosphine is undesirable. In collaboration with researchers in the NIST Chemical Science and Technology Laboratory, this project is developing a cavity ring-down spectroscopy technique to measure impurities with very low concentrations in semiconductor source gases. In this technique a high-finesse optical cavity is filled with the sample gas and then pumped with light that is strongly absorbed by the impurity molecule. The light is abruptly shuttered, and the decay time can be simply related to the impurity concentration. The advantages of this technique are that its accuracy relies primarily on accurate time measurement and detector linearity, and it is insensitive to absorption outside the cavity. The initial focus is on measuring water content in phosphine gas.

MILESTONE: By 2001, develop and prove cavity ring-down spectroscopy technique for measuring water in phosphine to 10 nmol/mol, calibrated to humidity standards.

Native oxide layers are having a significant impact on photonic devices due to their ability to provide both electrical and optical confinement, similar to native SiO_2 in integrated Si technology. They are used as confinement apertures and/or broadband antireflection (AR) coatings in vertical cavity surface emitting lasers (VCSELs), photodetectors, light emitting diodes, and saturable Bragg mirrors. In particular, the use of AlGaAs oxide apertures in VCSELs has resulted in record low threshold currents and high efficiencies. However, AlGaAs layers undergo a relatively large contraction during oxidation resulting in strain in the adjacent GaAs layers. This frequently causes structures to fail. This technique allows the identification of strains as small as 0.02 %, with lateral resolution on a nanometer scale. We will study how the strain in these structures varies as a function of the oxidation and post oxidation processing conditions. In addition to this, we will focus on a comparison of oxidation of AlGaAs layers grown by different techniques (MOCVD and MBE) and in different laboratories (government and industrial). Both techniques are used to grow devices containing native oxide layers, and understanding their similarities and differences may aid in the search for more stable, reliable oxide layers.

Oxidation furnace for forming oxide layers from epitaxially grown AlGaAs .

MILESTONE: By 2001 characterize and compare the oxidation of additional AlGaAs layers grown by MBE and MOCVD.

MILESTONE: By 2002 characterize the strain in GaAs layers adjacent oxidized AlGaAs layers.

The measurement of detector spectral responsivity is a service performed by the Optoelectronics Division. To provide an improved service with wider applicability and impact, we need to replace lasers that emit at discrete wavelengths and broadband lamp sources that have low output intensity with compact, broadly tunable lasers. We are developing semiconductor quantum well and quantum dot lasers that will allow us to reach the wavelength ranges between those of commercially available products in order to meet this need.

MILESTONE: By 2001, develop infrared tunable lasers with 100-300 nm tunability.

Collaborations with industrial, university and government laboratories leverage division resources and provide valuable feedback to our programs. Collaborations can range from the growth of a few device structures to multiyear Cooperative Research and Development Agreements (CRADAs).

Accomplishments

- The specimen set for composition accuracy studies tripled in number this year, leading to a significant expansion in our knowledge of uncertainties in multiple techniques. With this larger data set, collaborators in CSTL were able to show reproducible EMPA results with 2-sigma variation of 0.001 to 0.002 in mole fraction, and thus meet the precision goal of our to-be-developed composition standards. *In situ* data are often within 2 % of the EMPA analysis, but there are some exceptions that must be explored. The deviations observed so far exceed the short-term reproducibility of the measurements. Detailed studies of uncertainty in composition measurement from PL data showed that doping-related shifts in optical constants produce apparent composition shifts of up to 0.015 in mole fraction for Al(.2)Ga(.8)As specimens. Specimen temperature during PL measurement also has a small but measurable effect.

- MOCVD-grown InGaAsP samples of three different alloy compositions were obtained from industry, and a list of companies wishing to be included in the interlaboratory comparison study was developed. The samples were mapped using PL and X-ray. These preliminary measurements demonstrate that sample inhomogeneity is a very real issue; pieces for the interlaboratory comparison will be cleaved from the most uniform region of each sample.

- Cavity ringdown signals were observed for the first time this year in the system equipped for phosphine service. Coupling into the cavity is weak due to instabilities in the pump laser. CSTL collaborators designed and built a transfer cavity system and tested a new laser source to address these stability issues.

- Alloy composition, growth technique, and crystal direction were examined for their influence on the formation of native oxides from AlGaAs through wet thermal oxidation. Samples containing $Al_xGa_{1-x}As$ layers with x = 0.9 to 1 were oxidized for a range of times at 460°C. The oxidized layers were imaged by SEM and the depths of the oxidation fronts were measured from the images. Oxidation of MBE-grown layers was 1.5 to 3 times faster than that of MOCVD-grown layers for all compositions except 100% AlAs. The difference may be related to the fact that AlGaAs layers grown by MBE are actually pseudoalloys. It was found that pseudoalloys with AlAs layer thicknesses less than 4 nm had lower oxidation rates than those with thicker AlAs. For MBE samples with x = 0.98, differences in the oxidation depth along <001> and along <01-1> were dependent on oxidation time.

- Software for modeling tunable laser structures was purchased and used to design the first round of lasers. Lasers were grown and tested in preparation for mounting in an external cavity for full testing of the tunability range.

- NIST and Materials Research Source, LLC, signed a CRADA this year for the development of nanopatterned substrates for growth of ordered arrays of semiconductor quantum dots. Test runs on the initial batch of patterned silicon substrates indicate that the dot formation on these substrates proceeds without the formation of a wetting layer, a distinct contrast with unpatterned substrates.

- Collaborations with two university groups led to development of new types of semiconductor optical amplifiers and resonant-cavity photodetectors.

FY Deliverables

Publications

"AlGaAs Composition Measurements from *In Situ* Optical Reflectance"; K.A. Bertness, J.T. Armstrong, R.B. Marinenko, L.H. Robbins, A.J. Paul, J.G. Pellegrino, P.M. Amirtharaj, and D. Chandler-Horowitz; Conf. Dig., LEOS

Summer Topical on Optical Sensing in Semiconductor Manufacturing, Jul 24-28, 2000, Aventura, FL, 21-22; Jul 00.

"Smart Pyrometry for Combined Sample Temperature and Reflectance Measurements in Molecular-Beam Epitaxy"; K.A. Bertness; J. Vac.Sci. Technol. B 18(3): 1426-1430; May/June 00.

"In Situ Atomic Absorption with Substrate Reflection"; S.P. Hays, R.K. Hickernell, and K.A. Bertness, Proc., SPIE, Vol. 3946, Vertical-Cavity Surface-Emitting Lasers IV, Jan 24-28, 2000, San Jose, CA: 41-46; Jan 00

"Quantum Dot Semiconductor Optical Amplifiers"; R.P. Mirin and D.J. Blumenthal; OSA TOPS, Advanced Semiconductor Lasers and Their Applications 31: 183-185; Jul 00.

"High-Speed Resonant Cavity Enhanced Photodiodes"; M.S. Unlu, E. Ozbay, E. Towne, R.P. Mirin, and D.H. Christensen; Opt. And Phot. News 10(12): 13-14; Dec 99.

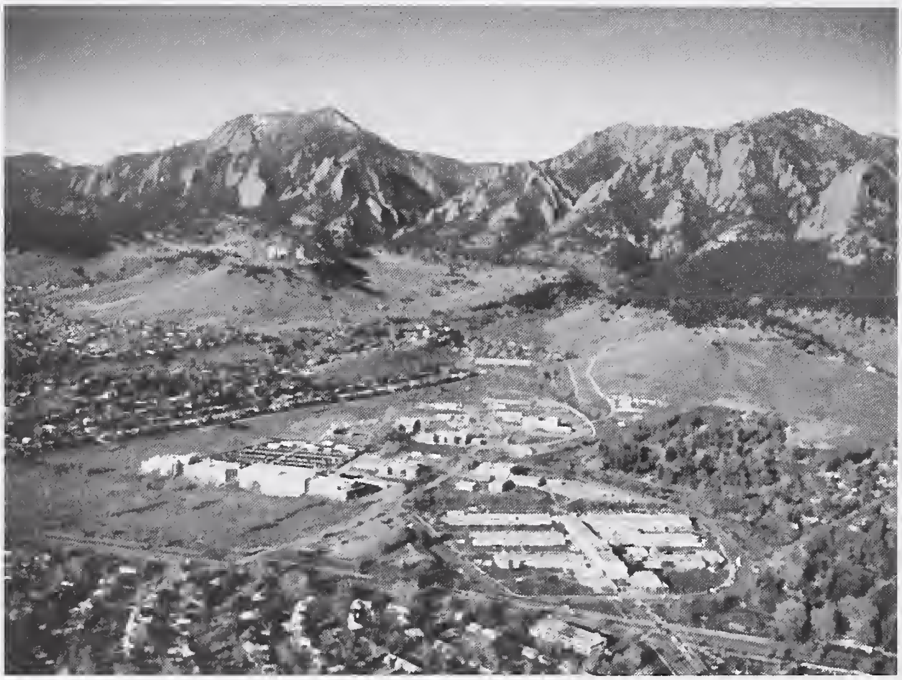
Appendix A: Major Laboratory Facilities

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 for the Optoelectronics Group.

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 and 193 nm), the Division has the only measurement capability in the world.



View of NIST Boulder Laboratories with backdrop of Boulder Mountain Parks

Appendix B: NRC Postdoc 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 postdoctoral 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 postdoctoral level for tenure as guest researchers at participating laboratories. The deadline for applications is January 15, 2002 for appointments beginning between July 1, 2002 and the following January 31, 2003.

The objectives of the Programs are:

- To provide postdoctoral 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 5 years of application. NRC positions involve a two-year tenure at NIST, and the salary paid in 2000 was $50,000.00.

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 may also visit the NRC Research Associateship Program Optoelectronics Division web page (http://national-academies.org/rap) to see a list of opportunities within our division.

Opportunities for the year 2001 with the Optoelectronics Division through the NRC Research Associateship program:

- Optical Fibers and Integrated Optics
- Dimensional Characterization of Optical Waveguides
- Nonlinear Properties of Single-Mode Optical Fiber
- Multimode Optical Fiber Bandwidth
- Materials Characterization for Optoelectronics
- Optoelectronic Materials Characterization by cw and Ultrafast Nonlinear Optics
- Ultrafast Widely Tunable Coherent Infrared and Ultraviolet Parametric Sources
- Femtosecond Metrology for Compact Photonic Devices
- Quantum Limited Laser Linewidths
- *In-Situ* Metrology of Epitaxial Crystal Growth for Semiconductor Optoelectronics
- Vertical-Cavity Optoelectronics
- Strained Heteroepitaxy for Compound Semiconductor Optoelectronics
- High Speed Optoelectronics Measurements
- Deep Ultraviolet Laser Metrology
- Fiber and Discrete Components
- Optical Data Storage
- Optical Fiber Sensor Systems
- Polarization Metrology

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 post-docs are employed by the University of Colorado or the Colorado School of Mines and normally carry out research at the NIST Boulder Laboratories.

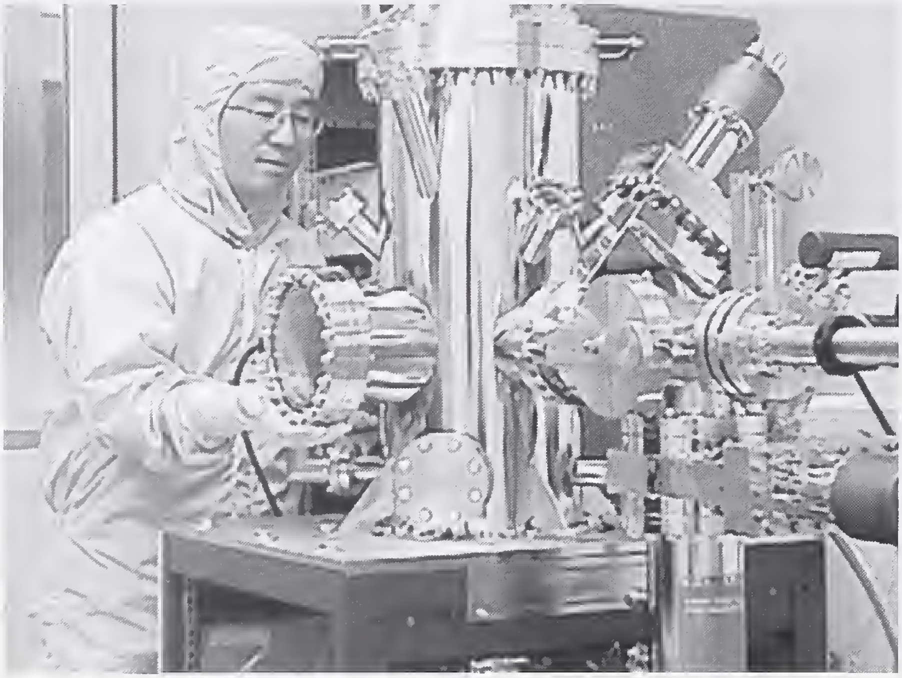
Students are usually hired just before the spring, fall, or summer terms, and may be employed for one or more terms. Post-docs may begin any time during the year. Applications are accepted throughout the year.

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. Postdocs 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



Post-doc Chulsoo Kim operating the chemically assisted ion-beam etching system for photonic crystal fabrication

Appendix C: Conferences and Workshops

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 in the fall of even-numbered years. This Symposium is a 2 ½ 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 guide 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
- Chromatic dispersion
- Cross talk
- Cutoff wavelength
- Effective area
- Effective index
- Four wave mixing efficiency
- Index of refraction profile
- Mode-field diameter
- Nonlinear coefficients
- Polarization dependent loss
- Polarization-mode dispersion

A limited number of Digests from previous Symposia are available. For information on obtaining a Digest or for information on upcoming Symposia, please contact the Optoelectronics Division Office or visit our web page, http://www.boulder.nist.gov/div815/current.html.

Laser Measurements Short Course

The Optoelectronics Division, in cooperation with the University of Colorado at Boulder, offers an annual Short Course on Laser Measurements. The 3 ½ day course emphasizes the concepts, techniques, and apparatus used in measuring laser parameters. A tour of the NIST laser measurement laboratories is included. The faculty consists of laser experts from NIST, industry, and other government agencies. A degree in physics or electrical engineering, or equivalent experience is assumed, and some experience in the use of lasers is desired for attendees.

Appendix D: Cooperative Research and Development Agreements (CRADAs)

CRADA Title: Deep Ultraviolet Laser Dose Measurement Service
CRADA Partner: International SEMATECH, Inc.
NIST Principal Investigators: Tom Scott, Marla Dowell

CRADA Title: Optical and Structural Examination of GaN Films
CRADA Partner: Astralux
NIST Principal Investigator: Norman Sanford

CRADA Title: Assess Rare-Earth-Doped Glasses as Waveguide Hosts
CRADA Partner: Schott Glass Technologies
NIST Principal Investigator: David Veasey

CRADA Title: Fiber Sensors
CRADA Partner: Texstar, Inc.
NIST Principal Investigator: Allen Rose

January 2001

For additional information contact:
Telephone: (303) 497-5342
Facsimile: (303) 497-7671
On the Web: http://www.boulder.nist.gov/div815