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Bibliography of the NIST Optoelectronics Division

Edited by
Annie J. Smith

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Annie J. Smith, Editor

INTRODUCTION

Gordon W. Day

The National Institute of Standards and Technology's (NIST's) Optoelectronics Division was established in 1994 to provide the optoelectronics industry with measurement technology, standards, and traceability to those standards. Optoelectronics research at NIST is not new, however. The Division's roots extend to the first work by NIST (then the National Bureau of Standards—NBS) on lasers—research begun in the early 1960s to develop techniques for measuring their output power or energy.

> Mission
> To provide the optoelectronics industry and its customers and suppliers with comprehensive and technically advanced measurement capabilities, standards, and traceability to those standards.

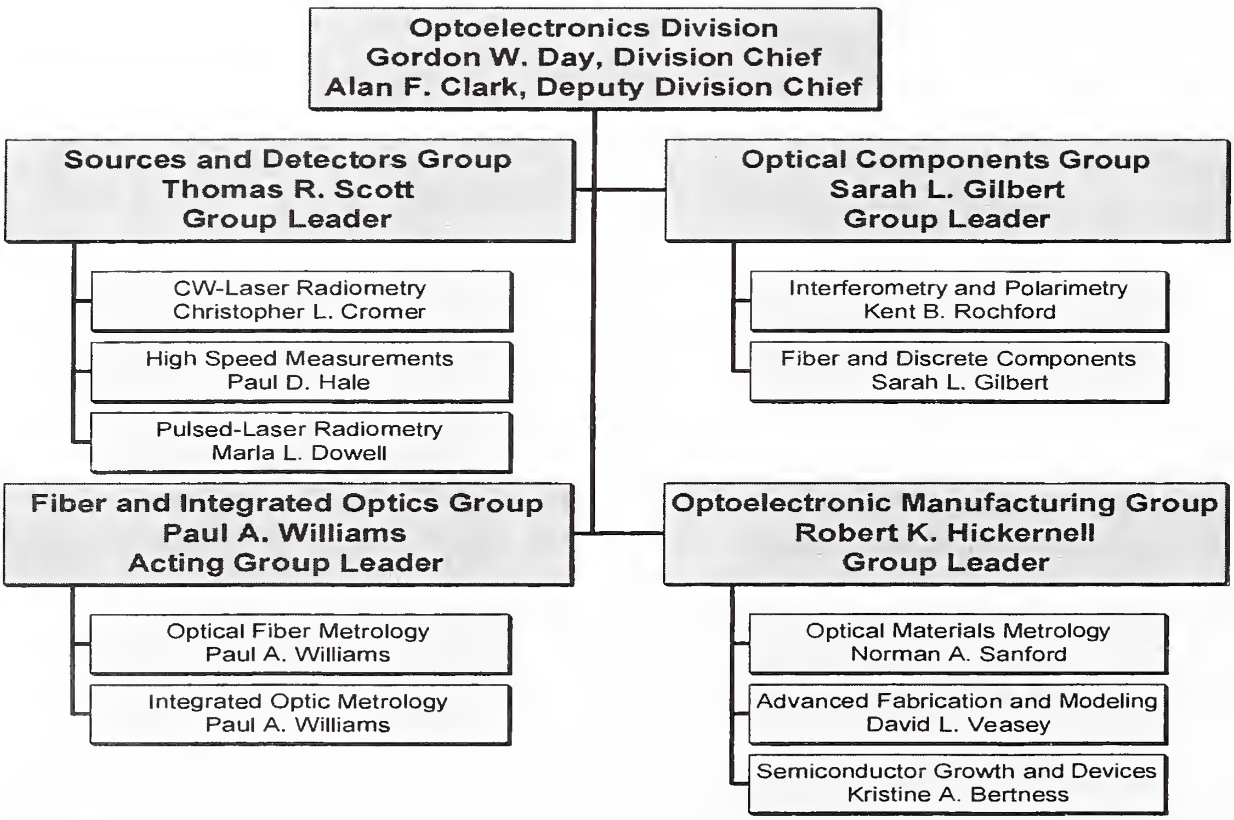
Laser characterization continues to be an important activity at NIST. The Optoelectronics Division maintains national standards for laser radiometry at a wide range of laser wavelengths, from the ultraviolet through the mid-infrared. The Division and its predecessor organizations have been providing measurement services for laser power and energy since 1967, and each year conduct more than 200 calibrations for about 50 customers. Many of these involve the calibration of an optical detector or power meter that will serve as a local standard at a customer's facility. Customers represent a wide range of applications where an accurate knowledge of laser output is important— materials processing, eye surgery, optical communications, and semiconductor lithography, to name a few.

In the mid-1970s work at NIST (NBS) in optoelectronics expanded to support the then-infant field of optical communications. At the time, optical fiber manufacturers were spending about 20 % of their production costs on measurements, and often could not agree with their customers on the characteristics of the fiber they sold. NIST has worked on these problems with manufacturers and users, primarily through industrial standards organizations. Today, measurement quality in the industry is much better and costs are much lower. Instrumentation of high quality for characterizing optical fiber is available commercially, and much of the Division's work has shifted to the development of artifactual standards to calibrate such instrumentation. As other, newer products pass through this cycle, the Division continues to assist, providing measurement expertise and often serving as a neutral party, in the development of voluntary industry standards.

High measurement costs are not acceptable in manufacturing, but better measurements can sometimes serve as a means of reducing manufacturing costs. Measurements made during manufacturing can be used to control the process more effectively, allowing more automation and leading to less waste and products of higher quality. Recognizing that these issues are particularly important in complex optoelectronic devices, the Division devotes a significant portion of its resources to the development of measurements for efficient manufacturing.

The Division maintains close connections to the optoelectronics industry. Division staff members represent NIST and the U.S. to the major domestic and international standards organizations active in optoelectronics—the Telecommunications Industry 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. The Division typically has several active Cooperative Research and Development Agreements (CRADAs) with companies and universities and is involved in 20 to 30 additional informal collaborations each year. The Division offers the optoelectronics community an annual short course on laser measurements and biennially organizes a major international conference on optoelectronic measurements, the *Symposium on Optical Fiber Measurements*.

The Division is organized into four groups: the Sources and Detectors Group, the Fiber and Integrated Optics Group, the Optical Components Group, and the Optoelectronic Manufacturing Group, which work in 10 project areas, as shown and described below.



CW-Laser Radiometry

The CW-Laser Radiometry Project develops measurement methods and standards for characterizing laser sources and detectors used primarily with cw radiation and develops and maintains measurement services for laser power and energy, optical-fiber power, and related parameters.

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, 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. In addition, special-test measurements are available for linearity, spectral responsivity, and spatial or angular uniformity of laser power meters and detectors. To meet the future needs of the laser and optoelectronics industries and to anticipate emerging technologies requires investigation and development of improved measurement methods and instrumentation for high-accuracy laser metrology over a wide range of power, energy, and wavelength.

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) that improves accuracy by an order of magnitude for laser-power measurements. To meet the increasingly demanding needs of higher accuracy, it is necessary to improve accuracy of calibration services through development of better transfer standards traceable to the LOCR.

In support of source characterization, measurement methods are developed to evaluate and reduce laser-intensity noise and to characterize the beam-intensity profile and propagation of laser beams. Advances in laser technology are continually producing a wider range of 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. Project members also 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.

High Speed Measurements

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 a bit rate of 5 to 10 gigahertz using pure time-division multiplexing (TDM). Laboratories around the world are doing research on the next generation TDM systems with a bit rate of 40 GHz. Methods are needed to characterize the frequency and impulse response of high-speed sources and detectors to at least the third harmonic of the system's modulation rate. Burst-mode operation, in asynchronous-transfer-mode networks, requires characterization at very low frequencies. Increasingly tight tolerances, in both digital and analog systems, require frequency-response measurements with low uncertainty. Design of high-speed optoelectronics systems requires measurement of the phase response of optoelectronic components. NIST has developed highly accurate heterodyne techniques for measuring detector frequency response and has calibration services available from 300 kHz to 50 GHz at 1319 nm and from 5 MHZ to 26 GHz at 850 nm. Researchers in the High-Speed Measurements Project are collaborating with industry and other groups within NIST to develop new techniques for measuring optoelectronic phase response with verifiable accuracy and for extending the frequency range of calibrations beyond 50 GHz.

Measurements of source and detector noise are required to predict low bit-error rates in computer interconnects, and high carrier-to-noise ratios in analog systems and to support erbium-doped fiber amplifier noise figure measurements. NIST is developing methods for calibrating optical-noise-measurement systems. The intensive use of laser target designators by the armed forces requires traceable calibration standards of low-level pulse power and energy at 1.06 μm and 1.55 μm. NIST has developed methods for calibrating absolute laser-pulse energy and peak power that are traceable to national CW laser power and energy standards maintained by the Sources and Detectors Group.

Pulsed-Laser Radiometry Project

The Pulsed-Laser Radiometry Project develops measurement methods and standards for characterizing pulsed laser sources and detectors. 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 the following areas: standards development, calibration services, and advising customers on in-house measurements. The bulk of the 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 correcting vision, 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. Increasing information-technology requirements have yielded a strong demand for faster logic circuits and memory chips of higher-density. 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 excimer-laser power and energy measurements at 193 nm and 248 nm.

There are a number of laser measurements that are important for both tool development and performance. Measurements at the source are used as part of a feedback mechanism to stabilize the source's pulse energy. Furthermore, there is an optimum laser dose that leads to the best resolution of small features at the wafer plane. When a photograph is taken, overexposure or underexposure of the object leads to reduced image contrast and poor resolution.

Optical material characterization measurements, such as transmittance and birefringence, are important for tool development and performance as well. Some materials are birefringent—orthogonally polarized light travels at different speeds as it propagates through these materials. Birefringence can be an inherent property of the material, or it can be introduced during the manufacturing process or by applying mechanical stress, such as clamping a mask. In particular, spatial variations across phase-shifting masks can lead to spatial variations across exposed wafers.

Optical Fiber Metrology

The Optical Fiber Metrology project develops measurement methods and Standard Reference Materials for optical fiber, and interacts with standards groups to provide a metrology base for the lightwave communication industry.

Optical fibers have largely replaced coaxial cable in long-distance telecommunications systems and are rapidly being installed in local-area applications. NIST staff interact with industry groups to develop measurement methods and reference standards for the characterization of these components. Connecting optical fibers together requires the fibers to have accurately controlled dimensions. Standard Reference Materials (SRMs) developed by NIST for cladding diameter, allow manufacturers to calibrate instrumentation used in manufacturing and quality control; geometrical standards for fiber coatings, connector ferrules, and mode-field diameter are also available as SRMs. Dispersion, the variation of propagation velocity with wavelength or polarization, sets a limit to the rate at which information can be transmitted; measurement methods and standards for chromatic dispersion are available, and polarization-mode dispersion standards are currently under development. The development of optical amplifiers has brought revolutionary changes to the design of communications; these new components require special methods of characterization, now in development. Nonlinear properties of fiber, such as four-wave mixing and solitons, have been studied and applied to instrumentation. Novel implementations of reflectometry in fiber are also studied. New methods of characterizing multimode fiber bandwidth, with application to high-speed, gigabit local-area data networks, have also been developed.

Integrated Optic Metrology

Optical waveguides in planar geometries, often called integrated optics, are increasingly used in communications and other optoelectronic systems. This Project develops measurement methods for integrated-optic waveguides. As more optical fiber is used in local-area networks and moves closer to the home and desk, more passive components, such as splitters and couplers, will be used. The trend toward wavelength-division multiplexing also adds to the demand for such components. Devices with large numbers of ports are likely to be less costly to produce using planar-waveguide technology rather than fiber technology. Several companies now manufacture or about to market 1 x N splitters using planar technology. There are, however, no standard measurement procedures or artifactual standards similar to those for optical fiber. Nor is it obvious how to perform analogous measurements since the mode-field pattern of an integrated optical waveguide is not circularly symmetric or since the normal fiber measurement is performed using a cutback technique. The Integrated Optic Metrology Project is using such tools as low-coherence reflectometry and refracted near-field scanning to address those measurement issues that are peculiar to planar waveguide geometries.

Interferometry and Polarimetry

This project develops polarimetric and interferometric systems to support optoelectronic industry measurement needs. We provide metrology and standards that improve the characterization of optical materials and components found in fiber-optic communications systems, fiber-optic sensors, and polarimetric instruments.

We recently began characterizing fiber Bragg gratings in response to the increased demands on these components in multiwavelength fiber systems. Using NIST developments in low-coherence interferometry, we have demonstrated improved measurements of grating group delay, dispersion, and spectral reflectance. We are applying this expertise and direct spectral measurements to develop standards for fiber Bragg grating sensors, improve industry test procedures, and characterize other optical components.

The Project provides measurements of materials and components and offers special measurement services for polarimetric quantities. For example, we work with an industry group to improve retardance measurements in optical discs. We are currently expanding our capabilities to include Mueller-matrix imaging polarimetry and provide measurements to the semiconductor industry. We also develop and evaluate new fiber optic sensor systems, components, and transducers for other government agencies and industry. When possible, newly developed sensor technology is transferred to interested U.S. companies.

Fiber and Discrete Components

Advanced optical-communications systems use many different types of components to control and modify propagating signals. The Fiber and Discrete Components Project develops measurement technology to characterize these components and understand their limits.

This project is currently conducting research on polarization-dependent loss metrology, optical-fiber photosensitivity, and wavelength standards for optical-fiber communications. Polarization-dependent loss in components affects a system's performance, especially when many components are in the system. We are developing a polarization-dependent loss calibration standard for commercial test instruments. Photo-induced Bragg gratings in optical fiber are important components of wavelength filters and dispersion compensators for wavelength-division multiplexed (WMD) optical-fiber communications systems, and are also excellent strain sensors. The project conducts research on the photosensitivity mechanism responsible for the grating inscription process in optical fiber and other materials. The project is also developing Standard Reference Material absorption cells for wavelength calibration in the WDM region. These cells can be used to calibrate the instruments that characterize the spectrum of sources and the wavelength dependence of components. This calibration capability will become increasingly important as more WDM optical communication systems are implemented.

Optical Materials Metrology

Newly emerging engineered-material systems offer great promise in optoelectronics. Gallium nitride (GaN), for example, is now regarded as the material of choice for high-powered visible light-emitting diodes (LEDs) and blue laser diodes. Wafer bonding of compound III-V semiconductors permits the heterogeneous integration of epitaxially incompatible materials, enabling, for example, electrically pumped 1550 nm vertical-cavity surface-emitting lasers (VCSELs) and high-powered LEDs. Nanoscale periodic dielectric structures, known as photonic crystal lattices, are contributing to the development of an entirely new family of integrated optical modulators, waveguides, wavelength-division multiplexing (WDM) filters, resonators, channel add/drop elements, and the eventual integration with optical micro-electromechanical (MEMs) devices. Quantum dots, embedded in photonic lattices, are leading to zero-threshold lasers and countable single-photon emitters via quantum-confined cavity effects.

More mature materials technologies, including $LiNbO_3$ and $LiTaO_3$ are now enjoying substantial economic impact due to the booming markets for components required for optical telecommunications. Devices fabricated from these materials include high-speed integrated optical modulators for >40 GHz data rates and periodically poled structures used in CW optical parametric oscillators that are widely tunable in the telecom wavelength bands. Additionally, periodically poled structures are also used in telecommunications for optical wavelength translators.

The Optical Materials Metrology Project is applying methods of nonlinear optics, optical spectroscopy, and ultrafast optics in order to characterize these materials and structures. Highly collaborative, the Project works closely with various laboratories, universities, and research institutes. For example, a recent study of $LiNbO_3$ combined nonlinear optical analysis methods with high-resolution x-ray diffraction imaging performed by the NIST Materials Science and Engineering Laboratory to correlate defect and composition uniformity with device performance. Nonlinear optical analysis, including second-harmonic generation, third-harmonic generation, and sum-frequency generation, are being used to investigate the surface and bulk uniformity of intrinsic and doped GaN in the form of bulk single crystals and thin epitaxial films. The interfacial uniformity of wafer-bonded compound III-V semiconductors is being investigated by both conventional and ultrafast nonlinear optical methods. Oxide/semiconductor interfaces are being similarly examined. The control of the spontaneous and stimulated emission rates of quantum dots embedded in photonic crystal structures is under investigation. Here, the quantum dots will be charged one electron at a time using a single-electron turnstile device at millikelvin temperatures.

Advanced Fabrication and Modeling

The mission of the Advanced Fabrication and Modeling Project is to develop and apply advanced photonic modeling, fabrication, and ultrafast measurement systems that support the achievement of industrial metrology and technology development goals. One objective is the development of an infrastructure within NIST for generalized modeling of photonic components and subsystems. Coupled with this objective is the verification of component models through targeted component fabrication, accurate measurement, and comparisons with other modeling algorithms. The initial focus of this effort has been on waveguide lasers, amplifiers, gratings, and photonic-bandgap structures.

A significant part of the Project's work involves the development of advanced optoelectronic devices for metrology and other applications. Compact and stable solid-state lasers are being developed for the measurement of frequency response in high-speed detectors and the characterization of components for wavelength-division multiplexing. Project members are fabricating mode-locked waveguide lasers for use in photonic analog-to-digital conversion applications. Ultrafast measurement capabilities over a broad spectral range support this effort through the characterization of carrier dynamics in semiconductor saturable absorbers. They also enable measurements of self-assembled quantum dots for lasers and amplifiers.

Semiconductor Growth and Devices

The Semiconductor Growth and Devices Project supports the III-V semiconductor optoelectronics industry with research related to epitaxial growth of III-V materials and fundamentally new device structures. Project members are working with industry to improve the accuracy of alloy composition measurements, in situ measurements during epitaxial growth, and measurements of impurity concentrations in semiconductor source materials to facilitate device modeling and to simplify the purchase of epitaxial growth services. Novel techniques are being developed to gain better control of self-assembled quantum dot materials and to use their unique properties in device structures. The materials properties of native oxides made from wet oxidation of AlGaAs are being studied for better understanding and control of their use in optoelectronic devices, particularly vertical cavity surface-emitting lasers. Project members are also collaborating with industry, other government laboratories, and universities to develop new types of widely tunable diode lasers, semiconductor optical amplifiers, large, highly ordered quantum dot arrays, and high-speed photodetectors.

Publications

This bibliography provides one means of access to the work of the Division. It includes most of the papers published by the Division and its predecessor organizations since 1970. A few important earlier papers and a few papers published by present NIST staff before they joined the Institute are included. The document is organized by subject, along the project lines defined above. It is updated annually. The references are presented in inverse chronological order, with the most recent first and are followed by an author index.

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Reprints of papers published in non-NIST media may be available in limited quantities from the authors.

A Note on Abbreviations

On August 23, 1988, the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST); therefore, documents with either prefix are considered NIST publications. Most readers are familiar with the commonly used abbreviations for the names of the professional journals that appear in this bibliography. Some publication series are peculiar to NIST and may call for explanation. They are:

NISTIR - NIST Interagency/Internal Report	NBSIR - NBS Interagency/Internal Report
NIST TN - NIST Technical Note	NBS TN - NBS Technical Note
NIST SP - NIST Special Publication	NBS SP - NBS Special Publication
NIST HB - NIST Handbook	NBS HB - NBS Handbook
NIST JRES - Journal of Research of the NIST	NBS JRES - Journal of Research of the NBS
NIST MN - NIST Monograph	NBS MN - NBS Monograph

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