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# Bibliography of the NIST Optoelectronics Division

Edited by
Annie J. Smith

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Annie J. Smith

Optoelectronics Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, Colorado 80303-3328

September 1999

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**TECHNOLOGY ADMINISTRATION,** Gary R. Bachula, Acting Under Secretary for Technology
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# A BIBLIOGRAPHY OF THE NIST OPTOELECTRONICS DIVISION

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 NIST (then the National Bureau of Standards—NBS) work on lasers—research begun in the early 1960s to develop techniques for measuring their output power or energy.

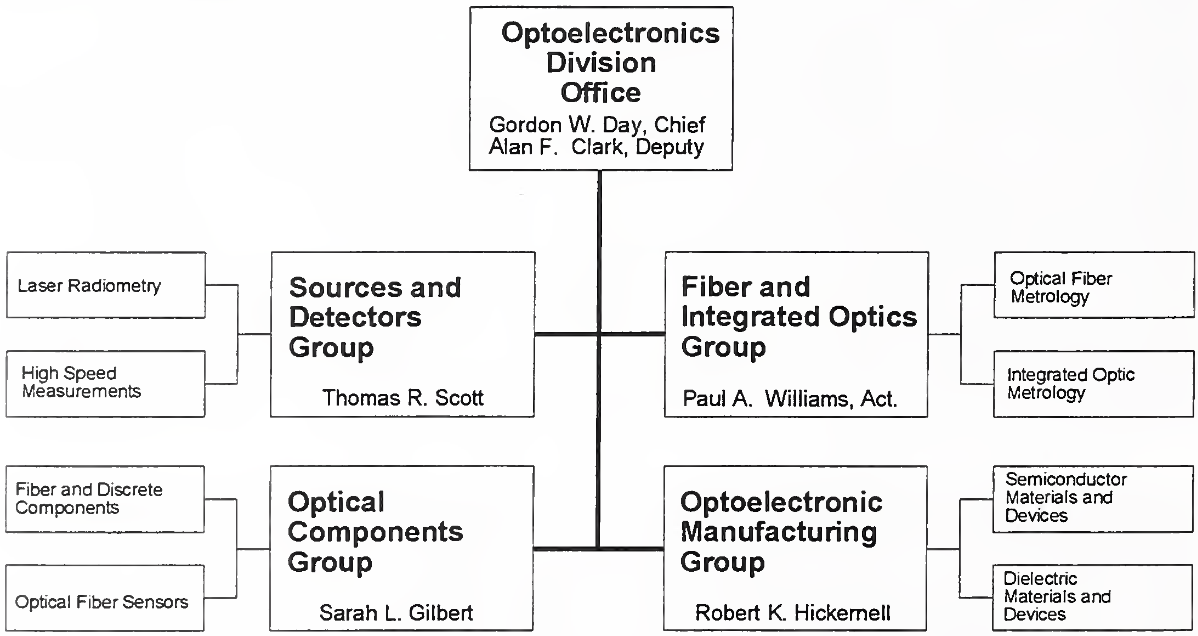
> Mission
> To provide the optoelectronics industry and its customers and suppliers with comprehensive and technically advanced measurement capabilities, standards, and traceability to those standards.

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 NIST's (NBS's) work 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 they 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 industry standards organizations. Today, measurement quality in the industry is much better and costs are much lower. High quality instrumentation for characterizing optical fiber is available commercially, and much of the Division's work has shifted to the development of artifact 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 higher quality products. 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 eight project areas, as shown above and described below.

## Laser Radiometry

The Laser Radiometry Project develops measurement methods and standards for characterizing laser sources and detectors used primarily with cw or pulsed 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, 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 reduce laser intensity noise, and to characterize beam intensity profile and propagation of laser beams. The semiconductor photolithography and corneal sculpting markets require pulsed excimer laser measurements. 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.

## High Speed Measurements

High-bandwidth measurements are needed to support high-performance systems which take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second (a bit rate of gigahertz) using pure optical time division multiplexing (OTDM). Research is being done on the next generation of OTDM systems at bit rates of 20 to 40 GHz in laboratories around the world. 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 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. NIST has developed highly accurate heterodyne techniques at 1319 nm and 850 nm for measuring detector frequency response. 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.

Source and detector noise measurements are required to predict low bit error ratios in computer interconnects, 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 low level pulse power and energy calibration standards at 1.06 µm and 1.55 µm. 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.

**Optical Fiber Metrology**

The Optical Fiber Metrology project develops measurement methods and Standard Reference Materials for optical fibers, 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. NIST-developed Standard Reference Materials (SRM) 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 the 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 to 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 1 x N splitters using planar technology or are about to market them. There are, however, no standard measurement procedures or artifact standards similar to those for optical fiber. Nor is it obvious how to perform analogous measurements when the mode field pattern of an integrated optical waveguide is not circularly symmetric or when 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 which are peculiar to planar waveguide geometries.

**Optical Fiber Sensors**

The NIST Optical Fiber Sensors project supports the optoelectronics industry by providing measurements and standards for the characterization of optical materials and components used in fiber optic sensors, communications systems, and polarimetric instruments. 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; one recent success is a commercially available current sensor made from common optical fiber that uses a process developed at NIST.

The polarimetry and interferometry expertise developed from sensor work is also applied to general component measurements. We are using low-coherence interferometry to characterize dispersion and other properties of fiber Bragg gratings. The Project has developed a Standard Reference Material for optical retardance and is working with industry groups to improve retardance measurements in optical discs and photolithography masks. We are developing capabilities in imaging Mueller -matrix polarimetry and offer special measurement services for retardance using the accurate methods developed at NIST.

**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.

## Dielectric Materials and Devices

NIST is developing measurement methods and acquiring critical materials data to improve the manufacturing of dielectric optical devices. Of current concern are the ferroelectric materials, lithium niobate and lithium tantalate, used in optical waveguide modulators, switches, and micro-lasers, and the glasses used in waveguide splitters, couplers, lasers, and optical amplifiers. Using nonlinear optical analysis, NIST researchers are measuring the compositional uniformity of substrate material and deposited layers. Rapid, nondestructive testing of uniformity across a wafer, or from wafer to wafer, aids substrate and device manufacturers in processing decisions which increase device yield. Additionally, various periodically poled structures for specialized frequency conversion applications, optical parametric oscillators (OPOs), etc., are under investigation. In collaboration with industry and with support from other governmental agencies, NIST is improving methods for the manufacture of compact, rare-earth-doped waveguide lasers and amplifiers. This work includes ultrafast passively mode-locked and Q-switched waveguide lasers.

Measurements of dopant diffusion and solubility in substrate material and the absorption and emission spectra of doped waveguides are combined with computer models to characterize the influence of glass chemistry, ferroelectric domain-reversed regions, and other critical parameters. Grating-based integrated optical components are gaining importance for wavelength division multiplexing, dispersion compensation, single-frequency lasers, and optical sensors. NIST scientists in the Dielectric Materials and Devices Project are studying the processing and metrology issues which lead to compact, robust cw and pulsed solid-state laser and nonlinear optical devices having high efficiency.

## Semiconductor Materials and Devices

The commercial success of semiconductor optoelectronic devices requires low-cost manufacturing for an ever-widening array of applications: telecommunications, computer interconnects, data storage, display, printing, and sensor systems. NIST scientists in this project develop measurement methods and provide data to support the efficient manufacture of devices such as diode lasers, light-emitting diodes, photodetectors, and modulators. They also invent and develop advanced devices to support research in NIST, other government agencies, and industry.

This Project is investigating the potential and limitations of optical instrumentation for the *in situ* monitoring of compound semiconductor epilayer deposition. Researchers correlate data from several *in situ* and *ex situ* measurement techniques to improve the measurement accuracy, with the goal of developing standard test procedures and reference materials. The project has begun to address the issue of impurity evaluation in source gases used for epitaxial deposition. Collaborative research has led to the high-resolution probing of vertical-cavity, surface-emitting laser (VCSEL) emission by near-field scanning optical microscopy, and to the measurement of the dielectric constants of native oxides used in VCSEL fabrication. Ultrafast pulse measurement capability is applied to materials characterization and next-generation, high-speed communications research. Researchers in this project fabricate semiconductor quantum well and quantum dot devices (in-plane lasers, VCSELs, high-speed resonant-cavity photodiodes, and saturable absorbers, for example) for use in metrology, sensing, and the understanding of manufacturing process limitations. The Optoelectronic Manufacturing Group combines its expertise to demonstrate hybrid integrated devices such as pulsed, solid-state waveguide lasers.

## 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 organization 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 followed by an author index

## Purchase Procedures

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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:

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

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