NIST United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 5065

A BIBLIOGRAPHY OF THE NIST OPTOELECTRONICS DIVISION

Edited by
Annie J. Smith

September 1997

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Optoelectronics Division
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Boulder, Colorado 80303-3328

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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) 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 (NBS) work on lasers–research begun in the early 1960s to develop techniques for measuring their output power or energy.

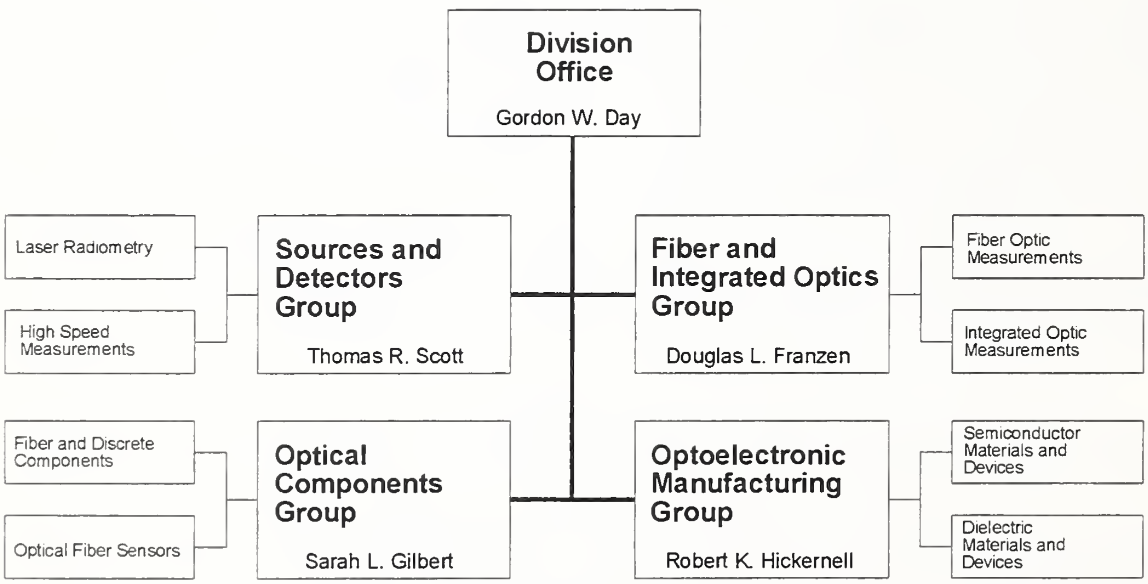
> Mission
> To provide the optoelectronics industry and its customers and suppliers with comprehensive and technically advanced measurement capabilities, standards, and traceability to those standards.

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 application areas 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') 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 a manufacturing process 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 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. 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 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/energy meters at commonly used wavelengths and powers. In addition, special test measurements are available for linearity, spectral responsivity, and spatial uniformity of optical 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 high resolution 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, and tunable-wavelength optical-fiber power measurement systems.

High Speed Measurements

The High Speed Measurements project provides advanced metrology, standards, and measurement services relating to temporal properties of optical sources and detectors used in association with optoelectronic systems.

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 (Gbit/s) using pure optical time division multiplexing (OTDM); research is being done on the next generation of OTDM systems at 20 to 40 Gbit/s. 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. 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 using electrical noise methods. Intensive use of laser target designators by the armed forces requires traceable low power and energy calibration standards for pulses at 1.06 μm and 1.55 μm.

Fiber Optic Metrology

The Fiber Optic 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. The joining of optical fibers requires the fiber to have accurately controlled dimensions. NIST-developed standard reference materials for cladding diameter allow manufacturers to calibrate instrumentation used in manufacturing and quality control; geometrical standards for fiber coatings and connector ferrules are being developed, as well. 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 are under development.

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 $1 \times N$ 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.

Optical Fiber Sensors

The NIST Optical Fiber Sensors project supports the sensor industry broadly by providing measurements and standards for the characterization of optical materials and components used in sensors. It also develops and evaluates new fiber optic sensors for other government agencies and industry. Most of its work has been devoted to high sensitivity, high bandwidth electric current and magnetic field sensing, though recent work has involved other measurands. A broad range of research and development is performed, including transducer, component, systems, and materials work. When possible, newly developed sensor technology is transferred to interested US companies. A successful example involves annealed fiber coil technology that creates stable current sensors from common optical fiber, and is now commercially available.

The Project has developed a Standard Reference Material for optical retardance, in collaboration with two U.S. companies. The device, based on Fresnel rhombs, will have nominally 90 ° retardance at 1.3 μm with 0.1 ° stability over wide ranges of wavelength, angle, and temperature. In addition to the Standard Reference Material, the project expects to 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 and gain metrology, characterization of photo-induced Bragg fiber gratings, and wavelength standards for optical fiber communications. Polarization-dependent loss and gain in components affect a system's performance, especially when many components are in the system. NIST is developing a polarization-dependent loss calibration standard for commercial test instruments and is characterizing polarization-dependent gain of fiber amplifiers. Photo-induced Bragg gratings in optical fiber are likely to be incorporated in fiber lasers, dispersion compensators, and filters, so the project evaluates the growth characteristics and long-term stability of these fiber gratings. The project is also developing Standard Reference Material absorption cells for wavelength calibration in the 1.5 μm region. These cells can be used to calibrate the instruments that characterize the spectrum of sources and wavelength dependence of components. This calibration capability will become increasingly important as wavelength division multiplexing optical communication systems are implemented.

Dielectric Materials and Devices

This Project is developing measurement methods and acquiring critical data to improve the manufacturing of dielectric optical devices and materials. This work supports current and eventual commercial applications requiring passive optical components, electro-optic and nonlinear devices, and compact solid-state lasers. Research activities include developing rapid nondestructive evaluation methods for bulk and thin-film optical materials such as lithium niobate, lithium tantalate, and potassium titanyl phosphate. Domain-engineered geometries of these materials are also under investigation. Commercial application of this work supports device and product development for optical data storage, biomedical lasers, vehicle navigation, and optical communications. NIST is also improving methods for the manufacture of compact rare-earth-doped solid-state waveguide lasers and amplifiers. This effort is currently emphasizing Nd-, Er-, and Yb-doped silicate and phosphate glasses. Critical measurements include evaluation of the dopant concentration profiles that define waveguides and spectroscopic properties such as lifetimes and cross sections. Rigorous numerical modeling is leading to optimized designs of mode-locked lasers, Q-switched lasers, and optical amplifiers. Various pulsed, cw, branched, and narrow-line lasers have been developed including distributed Bragg-reflector lasers. Commercial applications include sensors and optical telecommunications.

Semiconductor Materials and Devices

The commercial success of semiconductor optoelectronic devices in an ever-widening array of applications (telecommunications, computer interconnects, data storage, display, printing, and sensor systems) requires low-cost manufacturing. The Semiconductor Materials and Devices Project develops measurement tools suitable for critical manufacturing stages of compound semiconductor light-emitting diodes, diode lasers, detectors, and modulators. To improve wafer yield, the Project is studying optical methods for the in-process monitoring and control of semiconductor layer deposition. The operation of optoelectronic devices depends critically on the thickness and compositional uniformity of epitaxial layers. Project researchers use computer simulations and the correlation of data from several techniques –x-ray diffraction, transmission electron microscopy, reflectance spectroscopy, and photoluminescence spectroscopy–to improve the measurement accuracy. Test structures and novel measurement techniques have been developed to precisely measure optical constants, defect diffusion, and quantum microcavity effects. Researchers fabricate semiconductor quantum well devices for use in optical metrology and sensing. An ultrafast, ultrasensitive measurement system enables the characterization of material and structural properties which may limit ultimate device performance, and the verification of computer models of performance. In support of next-generation optical interconnect, display, and data storage products, NIST scientists are measuring the properties of surface-emitting 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.

Purchase Procedures

NIST (NBS) Technical Notes, Special Publications, Handbooks, Journals of Research, and Monographs may be purchased from the U.S. Government Printing Office at the following address: New Orders, Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954. Orders may be paid by major credit card, NTIS Deposit Account, or check or money order payable in U.S. dollars to the Superintendent of Documents. The Government Printing Office usually stocks these publications for only a year or two, after which they may be purchased from the National Technical Information Service at the address listed below. The GPO web site is http://www.access.gpo.gov/, (202) 512-1800.

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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 - NIST Journal of Research	NBS JRES - NBS Journal of Research
NIST MN - NIST Monograph	NBS MN - NBS Monograph

Acknowledgments

A large part of the labor of preparing a bibliography is spent collecting and arranging the material; Sheila Aaker, Frances Brown, Linda S. Derr, Edie DeWeese, Kit Kline, and Jessie Page assisted with these chores. The main sources of material were the NIST Boulder Editorial Review Board database, the National Technical Information Service, and information supplied by individual authors.

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