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The Boston University Photonics Center was established to conduct basic and applied research on photonics materials, devices, and systems related to defense needs, and to establish research laboratories and facilities to support collaboration among academia, industry, and DoD in a consortium of efforts in photonics for the New England area to (1) promote technological advances and commercializationin photonics; (2) support measures for the transfer of technology to DoD and industry; (3) prepare students for professional careers in photonics; and (4) promote economic development associated with a strong photonics industry. The resources and structure required for photonics technology development, product R&D, and the eventual commercialization of those technologies and products have been incorporated into the Photonics Center, and are described in this report.

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1.0 The Boston University Photonics Center

The Boston University Photonics Center was established in November, 1993 with funding support from Grant N00014-93-1-1186 administered by the Office of Naval Research and from Boston University. The Grant funding provided support for three core activities: the construction of a laboratory facility, the acquisition of capital equipment, and specific research and development projects. The enabling Grant established the Photonics Center as a self-sustaining organization with the mission:

- To conduct basic and applied research on photonics materials, devices, and systems related to defense needs.
- To establish research laboratories and facilities to support collaboration among academia, industry, and DoD in a consortium of efforts in Photonics for the New England area to:
  - promote technological advances and commercialization in photonics
  - support measures for the transfer of technology to DoD and industry
  - prepare students for professional careers in photonics
  - promote economic development associated with a strong photonics industry

Prior to the establishment of the Photonics Center, significant basic research in a variety of photonics technologies was being conducted by individual University researchers across the campus. The formal establishment of the Photonics Center provided an application focus for the previous research and added the role of photonics technology commercialization through an emphasis on prototype product development in formal partnerships with industry and DoD. In short, the Photonics Center is a resource that serves as a bridge between basic research and defense and industrial applications.

The resources required for photonics technology, product R&D, and the eventual commercialization of those technologies and products have been incorporated into the Photonics Center. As depicted in Figure 1-1, these resources include people, laboratory facilities and equipment, technology innovations, and links with business. The Photonics Center has recruited a full-time staff that includes engineering personnel with experience in DoD and commercial technology and product development, personnel with experience in the business aspects of bringing new products to market, and administrative support. The full-time staff is complemented by Members of the Photonics Faculty that include 46 faculty engaged in photonics research and development. Representing science (physics, chemistry, astronomy, biology) and engineering (electrical, aeronautical/mechanical, manufacturing, and biomedical) departments of the University's colleges, the Members of the Photonics Faculty provide broad scope and depth in photonics technology development.

The laboratory facilities for conducting the technical efforts can be grouped as materials and devices laboratories, systems development laboratories, and instrumentation laboratories, thus covering the various aspects of technology and product synthesis, design, fabrication, and characterization. Further, these laboratories have been established with particular attention to assuring the necessary capital equipment and expertise will be available to move photonics technology from concept demonstration to prototype product development.

Technical innovation is represented within the Center by the development projects it conducts both internally and in partnership with industry and DoD. These projects cover a broad range of photonics technology areas including: optoelectronics materials and devices, portable spectroscopy, advanced instrumentation, visible and infrared near-field optics and applications, quantum optics, LCD modeling and fabrication, medical diagnostics and treatment using photonics, organic dyes for photochromic and laser applications, and magneto-optic materials and devices, among others. The business services contained within the Photonics Center include incubator space for joint prototype product development with industry and start-up companies, as well as access to market survey, planning, management, and professional services that provide the needed economic and business infrastructure for fully exploiting new technology development. Together, the various entities bring the ability to develop new photonics technology and products needed by DoD and industry and help to assure a strong domestic photonics industry that will provide access to technology by DoD for its needs. The remaining sections of the report will expand on the various entities within the Photonics Center.

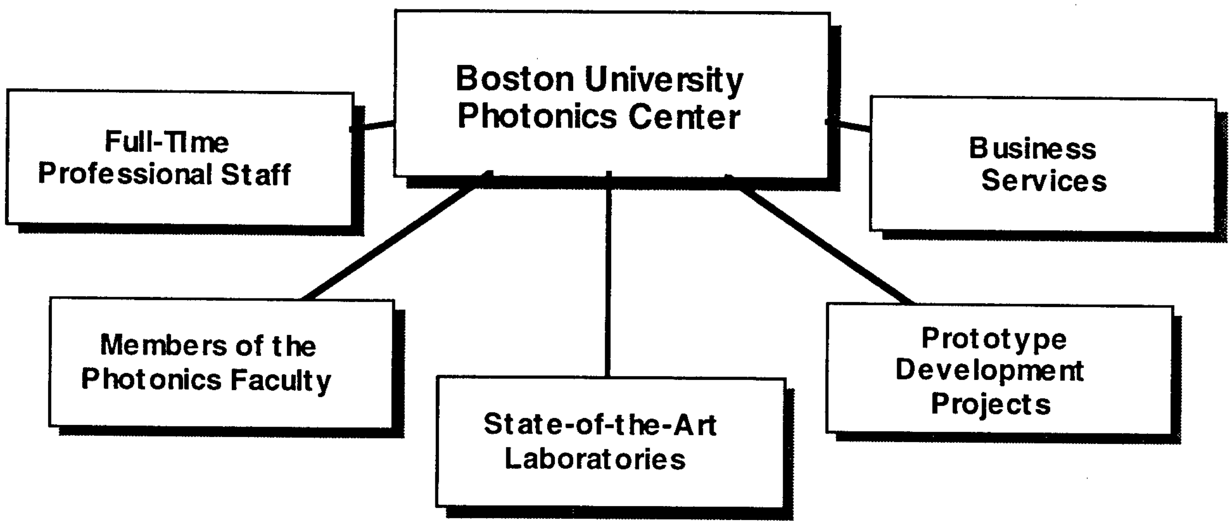


Figure 1-1
The Boston University Photonics Center Infrastructure

The Grant provided specific funding of $16,000,000 for construction of a new laboratory facility, $4,764,748 for purchase of laboratory capital equipment, and $8,235,252 for research and development and Center operation. Under the terms of the Grant, Boston University was required to provide a formal cost match of $16,000,000 to the construction funds. The University has met and exceeded its obligations for cost matching for construction of the new laboratory facility by providing approximately $63,600,000 for construction and has additionally provided funding of over $3,000,000 for operation of the Photonics Center.

2.0 Photonics Center Full-Time Staff and Affiliated Faculty

2.1 Center Staff

A key resource for effective partnering with industry to perform prototype product development is the full-time staff. Led by the Center's Director, Dr. Donald C. Fraser, former Principal Deputy Undersecretary of Defense for Acquisitions at the Department of Defense and former Executive Vice-President of Draper Laboratory, the full-time staff members are responsible for assuring that development projects conducted with our industry partners are conducted in an efficient manner with particular attention to meeting the cost and schedule requirements associated with successful prototype product development. In addition to a Deputy Director, the technical staff consists of eight full-time personnel. All have joined the Photonics Center from industrial or government contract development backgrounds and have in-depth experience in high-tech prototype product development, and business and project management. The technical staff includes both systems engineers who have a broad view of the application of new technology to new products as well as engineers who have a more specialized knowledge of photonics technologies such as optoelectronics materials and device fabrication, laser applications, and precision measurement techniques. Joining the technical staff are two staff members with experience in program management who act as liaison to the business and investment community to assure that joint university/industry prototype development projects meet business as well as technical goals. Table 2-1 identifies the full-time staff of the Photonics Center and indicates those members who received partial funding under the Grant.

Table 2-1
Boston University Photonics Center Staff

Dr. Donald C. Fraser*
Director

Dr. Paul R. Blasche*
Deputy Director

Ms. Barbara Haacke*
Senior Administrator

Mr. John Marenghi
Business Development

Mr. Cliff Robinson
Special Assistant to the Director

Engineering Staff:

Dr. James E. Hubbard*
Senior Systems Engineer

Dr. Shawn E. Burke*
Senior Systems Engineer

Mr. Peter McDonald
System Engineer

Dr. Ze'ev Feit
Photonics Engineer,
Optoelectronic Materials

Ms. Anlee Krup
Photonics Engineer,
Precision Measurements

Mr. Paul Mak
Photonics Engineer,
Optoelctronics Device Processing

Open Position
Photonics Engineering

Dr. Dingxue Yan*
Research Scientist

Support Staff:

Ms. Leigh Hallisey*
Administrative Assistant

Open
Building Coordinator

* Partially funded by Grant

2.2 Members of the Photonics Faculty

A cornerstone of the technology development capabilities at the Photonics Center is the breadth and depth of the University's faculty who hold appointments as Members of the Photonics Faculty. The Photonics Faculty includes 46 faculty members from the science departments (physics, chemistry, biology, astronomy) and engineering departments (electrical, aeronautical/mechanical, manufacturing, and biomedical) in the University's colleges. Each faculty member is appointed to the Photonics Faculty on a yearly basis by the Provost of the University. They provide a broad coverage of detailed technical knowledge for photonics developments including optoelectronics materials and devices, remote spectroscopy instrumentation, visible and infrared near-field optics and applications, quantum optics and applications, LCD modeling and fabrication, applications of photonic techniques to medical diagnostics, organic dyes for photochromic applications, and magneto-optic materials and devices, among others. In addition, three faculty members from the School of Management hold appointments as Members of the Photonics Faculty to ensure that business-related activities such as market surveys and business plans are carried out in conjunction with the technical program. The Photonics Faculty for the 1997/1998 academic year are listed in Table 2-2 which also indicates those Photonics Faculty Members receiving funding under the Grant for specific photonics technology developments to be described in Section 4.

Table 2-2

1997/1998
Boston University Photonics Center Faculty

College of Arts and Sciences

Astronomy:

Supriya Chakrabati*, Director, Center for Space Physics
Professor, Department of Astronomy and Center for Space Physics
Ph.D. University of California, Berkeley

Biology:

Phillip S. Lobel, Associate Professor, Department of Biology
B.A. with High honors (Zoology), University of Hawaii at Manoa, 1975
Ph.D. in Biology, Harvard University, 1979

David Shepro, Professor, Departments of Biology and Surgery
Ph.D., Boston University, 1959

Chemistry:

Charles Brecher, Research Professor, Department of Chemistry
B.A., Columbia University, 1954
M.A., Columbia University, 1955
Ph.D., Chemistry, Columbia University, 1959

Richard Clarke*, Professor, Department of Chemistry
Ph.D. University of Pennsylvania, 1969

Morton Z. Hoffman, Professor, Department of Chemistry
A.B. (cum laude), Hunter College of the City University of New York (major in Chemistry, minor in Physics and Mathematics), 1955
M.S., Chemistry, University of Michigan, 1957
Ph.D., Chemistry, University of Michigan, 1960

Guilford Jones*, II, Professor, Departments of Chemistry, Biophysics, and School of Medicine
B.S., Rhodes College, 1965
Ph.D., University of Wisconsin, 1970

Jonathan Lee, Chemistry, Assistant Professor, Department of Chemistry
Ph.D., The Ohio State University, 1986

Alexander Lempicki*, Research Professor, Department of Chemistry
Ph.D. University of London, 1960

Boris Levy, Research Professor, Department of Chemistry
B.A., Ph.D, Physical Chemistry, New York University,

Norman Lichtin, University Professor Emeritus and Professor Emeritus of Chemistry
Ph.D. Harvard University, 1948

Thomas David Tullius, Professor and Chairman, Department of Chemistry
B.S., Chemistry (cum laude), UCLA, 1973
Ph.D., Chemistry, Stanford University, 1979

Lawrence David Zeigler*, Professor, Department of Chemistry
B.S., SUNY at Stoneybrook, 1971
M.S., Physical Chemistry, Cornell University, 1974
Ph.D, Physical Chemistry, Cornell University, 1978

Physics:

Shyamsunder Erramilli*, Assistant Professor, Princeton University, Member, Princeton Materials Institute
B. Sc., Physics and Math, University of Pune, 1977
M.Sc., Physics, Indian Institute of Technology, 1979
Ph.D., Physics, University of Illinois, 1986

Bennet B. Goldberg*, Associate Professor, Department of Physics
B.A., Physics, Harvard University, 1982
Sc.M., Physics, Brown University, 1984
Ph.D., Physics, Brown University, 1987

Claudio Rebbi, Professor, Department of Physics
B.S., M.S., Ph.D., Nuclear Physics, University of Turin, 1967

Kenneth J. Rothschild*, Professor, Department of Physics; Director, NIH Molecular Biophysics Training Program; Director, Molecular Biophysics Laboratory
B.A., Physics, Rensselear Institute of Technology, 1969
Ph.D., Physics, Massachusetts Institute of Technology, 1974

William John Skocpol*, Professor, Department of Physics
B.A., Physics, Michigan State University, 1968
M.A., Physics, Harvard University, 1971
Ph.D., Physics, Harvard University, 1974

William A. Worstell*, Assistant Professor, Department of Physics
B.A., cum laude, Applied mathematics, Harvard College, 1980
Ph.D., Physics, Harvard University, 1986

College of Engineering

Aerospace and Mechanical Engineering:

Thomas Gary Bifano*, Associate Professor, Department of Aerospace and Mechanical Engineering; President, Prism Corporation
BS, Mechanical Engineering and Materials Science, Duke University, 1980
MS, Mechanical Engineering and Materials Science, Duke University, 1983
Ph.D., Mechanical Engineering, North Carolina State University, 1988

Shawn Burke, Senior Systems Engineer, Photonics Center; Research Assistant Professor, Department of Aerospace and Mechanical Engineering
B.S.E., Mechanical & Aerospace Engineering, Princeton University, 1981
M.S., Mechanical Engineering, Massachusetts Institute of Technology, 1983
Ph.D., Mechanical Engineering Massachusetts Institute of Technology, 1989

Steven Clark Fawcett, Associate Research Professor, Department of Aerospace and Mechanical Engineering; President/Senior Consultant, Muse Associates
B.S., Mechanical Engineering, North Carolina State University, 1985
M.S., Mechanical Engineering, North Carolina State University, 1988
Ph.D., Mechanical Engineering, North Carolina State University, 1991

Donald C. Fraser, Director, Photonics Center; Professor, Departments of Engineering and Physics
S.B., Aerospace Engineering, Massachusetts Institute of Technology, 1962
S.M., Aerospace Engineering, Massachusetts Institute of Technology, 1963
Sc.D., Massachusetts Institute of Technology, 1967

James E. Hubbard, Senior Systems Engineer, Photonics Center; Research Associate Professor, Department of Aerospace and Mechanical Engineering
B.S., Mechanical Engineering, Massachusetts Institute of Technology, 1977
M.S., Mechanical Engineering, Massachusetts Institute of Technology, 1979
Ph.D., Massachusetts Institute of Technology, 1982

M. Edward Womble, Research Professor, Aerospace and Mechanical Engineering
BSEE, Auburn University
MSEE, Auburn University
Ph.D., Massachusetts Institute of Technology

Biomedical Engineering:

Charles R. Cantor, Professor of Biomedical Engineering and Biophysics; Director, Center for Advanced Biotechnology; Professor, Pharmacology Department, Boston University Medical School; Chair, Department of Biomedical Engineering
A.B., Columbia University, Summa Cum Laude, 1963
Ph.D., University of California, Berkeley, 1966

Herbert F. Voigt, Associate Professor, Biomedical Engineering
B.E., Electrical Engineering, The City College of CUNY, 1974
Ph.D., Biomedical Engineering, Johns Hopkins University, 1979

Electrical and Computer Systems Engineering:

Roscoe C. Giles, Associate Professor, Department of Electrical and Computer Engineering, College of Engineering
B.A., Honors, Physics, University of Chicago, 1970
M.S., Physics, Stanford University, 1973
Ph.D., Physics, Stanford University, 1975

Allyn Hubbard*, Associate Professor, Departments of Electrical and Computer Engineering and Biomedical Engineering
B.S., Electrical Engineering, University of Wisconsin,1970
M.S., Electrical Engineering, University of Wisconsin, 1971
Ph.D., Electrical Engineering, University of Wisconsin, 1977

Floyd Bernard Humphrey, Research Professor, Department of Electrical, Computer and Systems Engineering
B.S., Chemistry, California Institute of Technology, 1950
Ph.D., Chemistry and Physics, California Institute of Technology, 1956

Thomas G. Kinkaid*, Associate Dean, College of Engineering; Professor, Electrical and Computer Engineering
B.S., Engineering Physics, Queen's University, 1959
S.M., Electrical Engineering, Massachusetts Institute of Technology, 1962
Ph.D., Electrical Engineering, Massachusetts Institute of Technology, 1965

Thomas D.C. Little, Associate Professor, Department of Electrical and Computer Engineering
B.S., Biomedical Engineering, Rensselaer Polytechnic Institute, 1983
M.S., Electrical Engineering, Syracuse University, 1989

Theodore D. Moustakas*, Professor, Department of Electrical, Systems, and Computer Engineering
B.S., Physics, Aristotle University, 1964
Ph.D., Solid State Science and Engineering, Columbia University, 1974

Michael F. Ruane*, Associate Professor, Department of Computer and Electrical Engineering,
B.E.E., Villanova University, 1969
S.M.E.E., , Massachusetts Institute of Technology, 1973
Ph.D. , Systems Engineering, Massachusetts Institute of Technology, 1980

Bahaa E.A. Saleh*, Professor and Chairman, Department of Computer and Electrical Engineering
B.S. honors, Electrical Engineering, Cairo university, Egypt, 1966
Ph.D. (distinction), Electrical Engineering, Johns Hopkins University, 1971

Alexander Vladimir Sergienko, Assistant Professor, Department of Electrical and Computer Engineering
M.S., Physics, Moscow State University, 1981
Ph.D., Physics, Moscow State University, 1987

E. Fred Schubert*, Professor, Department of Electrical and Computer Engineering
M.S. with honors, University of Stuttgart, 1981
Doctorate in Engineering with honors, University of Stuttgart, 1986

Johannes G. Smits*, Associate Professor, Department of Electrical, Computer, and Systems Engineering; Director, Sensors, Actuators and Micromechanics Laboratory
Doctorandus in Physics, University of Leyden, the Netherlands, 1970
Ph.D., Electrical Engineering, Twente University of Technology , The Netherlands, 1978

Malvin Carl Teich*, Professor, Department of Computer and Electrical Engineering, Biomedical Engineering, and Physics
S.B., Physics, Massachusetts Institute of Technology, 1961
M.S., Electrical Engineering, Stanford University, 1962
Ph.D., Cornell University, 1966

M. Selim Unlu*, Assistant Professor, Department of Electrical and Computer Engineering
B.Sc., Electrical and Electronics Engineering, Middle East Technical University, Turkey, 1986
M.S., Electrical Engineering, University of Illinois, Urbana-Champaign, 1988
Ph.D., Electrical Engineering, University of Illinois, Urbana-Champaign, 1992

Manufacturing Engineering:

Soumendra Nath Basu*, Associate Professor, Department of Manufacturing Engineering
B.Tech., Mechanical Engineering, Indian Institute of Technology, 1982
M.S., Ceramics and Material Science, 1985
Ph.D., Materials Science, Massachusetts Institute of Technology, 1989

Peter Z. Bulkeley, Professor Emeritus (active), Manufacturing Engineering
A.B., Mathematics, Bowdoin College
B.S., M.S., Mechanical Engineering, Massachusetts Institute of Technology
Ph.D., Engineering Mechanics, Stanford University

Vinod K. Sarin, Professor, Department of Manufacturing Engineering
B.Sc., Metallurgical Engineering, University of Wisconsin, 1965
M.Sc., Metallurgical Engineering, University of Michigan, 1966
Sc.D., Metallurgy, Massachusetts Institute of Technology, 1971

School of Management:

Peter Arnold, Associate Professor, Operations Management, Boston University School of Management
B.S., Transportation, Northeastern University, 1982
M.B.A. Operations Management, Indiana University, 1985
Ph.D., Operations Management, 1989

J. Robb Dixon, Associate Professor of Operations Management, Metropolitan College and School of Management
B.A., Biology, Wesleyan University, 1974
M.B.A., Darden School, University of Virginia, 1981
Ph.D., Operations Management, Darden Graduate School of Business Administration, University of Virginia, 1987

Barry Unger, Associate Professor of Innovation and Technology, Metropolitan College
S.B., Massachusetts Institute of Technology
Ed.D., Harvard University

* Received partial Grant funding for specific technology development.

3.0 Photonics Center Building

3.1 Building Overview

A major effort under this Grant has been the design and construction of a state-of-the-art laboratory facility to house the Photonics Center. The newly constructed Photonics Center Building, located on the Boston University Campus at 8 Saint Mary's Street, and shown in Figure 3-1, was occupied beginning in July, 1997 following a 39-month design and construction effort. Light is the prevailing design theme throughout the building, while functionally the emphasis is to provide broad-purpose laboratory facilities to meet the needs of collaborative teams of academic, industry, and government researchers for the development of photonics technologies and products.

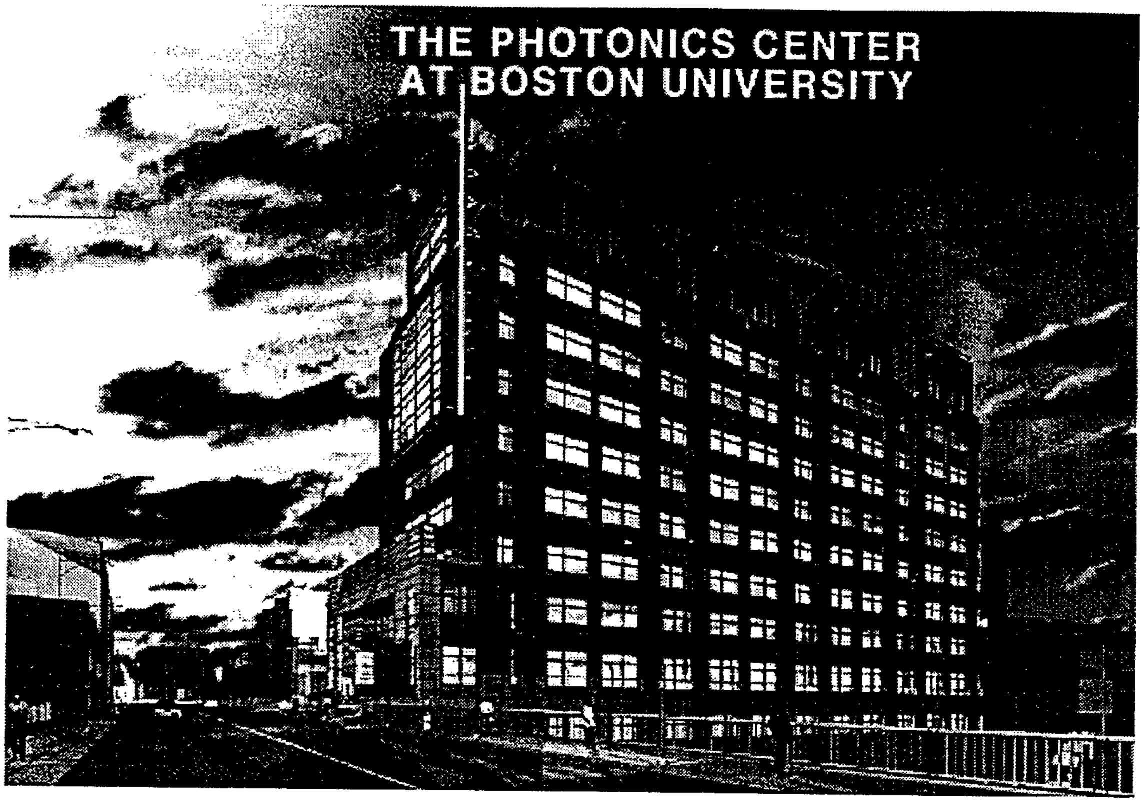


Figure 3-1

Boston University Photonics Center Building

The facility is ten stories tall with a basement and is programmed as:

Floor 10-11	Mechanical Penthouse
Floor 9	Administration, Photonics Laboratories, Colloquium
Floor 8	Photonics Laboratories
Floor 7	Photonics Laboratories
Floor 6	Incubator Facility (shell)
Floor 5	Engineering Research
Floor 4	Engineering Research
Floor 3	Engineering Research
Floor 2	Engineering Research, Classrooms
Floor 1	Teaching Laboratories
Basement	Photonics Laboratories

The basic structure of the building sits on an approximately 6 foot thick concrete mat to minimize vibrations throughout the building that would otherwise be deleterious to optical developments and precision measurements. The mechanical penthouse, in addition to standard HVAC services, contains the specialized services required for a technology development laboratory including chilled water, vacuum, pressurized air, and ventilation for fume hoods.

The photonics laboratories provide fully-permitted research and development facilities for a number of specialty areas in photonics, including materials and device development, component and systems development, and advanced instrumentation. A brief description of the laboratory facilities follows later. These descriptions within include summary lists of major equipment, a portion of which was purchased under the Grant.

The engineering research laboratories are currently occupied by the Electrical and Computer Engineering Department, but were designed for eventual expansion of the Photonics Center. The Incubator Facility has been set aside for occupation by industry partners of the Photonics Center engaged in joint product development programs. A thumb-nail sketch of building specifics includes:

Building Area	285,000 gross square feet 160,000 net square feet
Clean Room Area	Class 100: 798 net square feet Class 1,000: 1,595 net square feet Class 10,000: 1,540 net square feet
Number of Fume Hoods	30
Business Incubator area	25,000 gross square feet
Ventilation Capacity	444,000 cubic feet per minute
Total Installed Cooling	23,000 million BTU/H
On-site Electrical Sub-station	16 watts per square foot (doubly redundant)
Structural Concrete Mat	4,815 cubic yards

3.2 Cost Share

Under the terms of the Grant, Boston University committed to a formal cost match of $16 million for construction of the Photonics Center Building to supplement the $16 million provided by the Grant. Total cost of the building project was approximately $79,600,000. While the Photonics Center controls use of the entire building, it currently occupies approximately 60% of the building. Total cost of construction of the area currently occupied by the Photonics Center was therefore approximately $43,760,000 . Therefore, Boston University exceeded it formal cost match requirements under the Grant by $15,760,000.

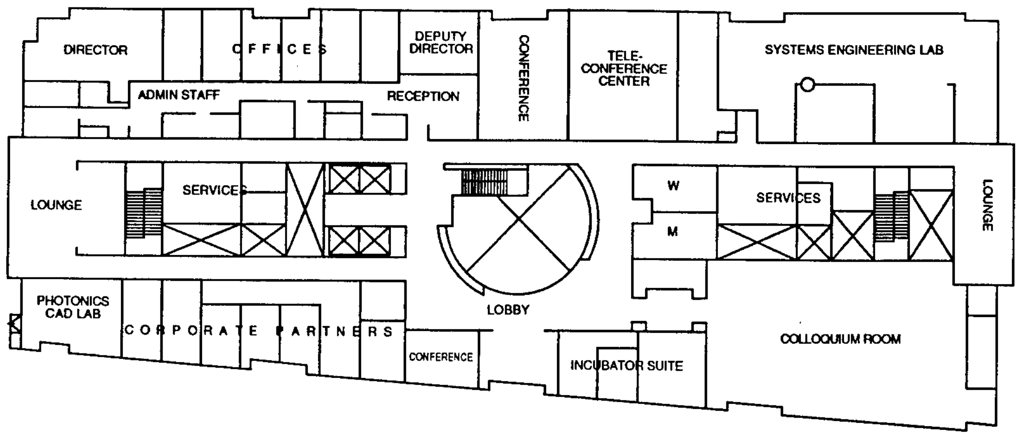
3.3 Photonics Center Facilities

3.3.1 Ninth Floor

The ninth floor houses a variety of functions for the Photonics Center including:

- Office space for Photonics Center administrative and engineering staff.
- Office space for companies working on joint photonics product development projects with the Center.
- A video conference facility for the Center's use and for use by its industry partners in conducting the necessary level of communications required for joint engineering development projects. Featuring PictureTel video conference equipment, this facility provides the ability to have "face-to-face" project and technical interchange meetings as well as providing a facility to support distance learning for educational purposes.
- A Colloquium Room seating approximately 200 people.

In addition, the System Engineering Laboratory and the Photonics Computer-Aided Design Facility reside on the ninth floor.



9th FLOOR

Figure 3-2
Photonics Center Building Ninth-Floor Layout

3.3.1.1 Photonics Systems Engineering Laboratory:

The Photonics Systems Engineering Laboratory provides the facility, equipment, and expertise to design, develop, and characterize photonics based systems for a wide variety of commercial applications. Our products are engineering prototypes of the systems and information generated during their development and characterization. The Systems Laboratory supports developments for both Photonics Center applications as well as those of our industrial partners.

The Systems Laboratory operates within the Center at a number of levels. Fundamentally it serves as an adjunct to other laboratories within the Center, integrating the technology developments from these focus laboratories into prototype systems. It provides the home for development, implementation, and characterization of specific photonic-based systems for specific applications. And finally, it provides a common site for optical and electronic instrumentation used to characterize photonics systems as well as serve the additional needs of some of the focus laboratories. Optical and photonics components are available for prototyping and characterizing systems over the ultraviolet-visible-infrared wavelengths, along with vibration isolated test stations, high-bandwidth electronics, and data acquisition equipment. In addition to photonics and electro-optics test and measurement instrumentation, the Systems Laboratory includes a laminar flow hood, a fume hood, vacuum oven, a wide assortment of mechanical and electrical materials, complete assortment of tools, a mechanical CAD workstation, and machining and electronics fabrication capability as an adjunct to the University's machine and electronics fabrication shops that are available to the Center.

Major Equipment:

- Electro-Optical Components
  - 1" and 2" circular lenses; achromatic lenses
  - Cylindrical lenses
  - Mirrors; retroflectors
  - Bases, posts, lens holders
  - Rails and mounts
  - Optical breadboards
  - Cube and pellicle beamsplitters
  - Prisms
  - 1/4 and 1/2 wave plates (zero order)
  - Beam expanders
  - Collimators
  - Glan-Thompson polarizing prisms
  - Neutral density, 10-nm BW, color, and 40-nm BW filters
  - 1- and 2-axis positioners; goniometers
  - Lab jacks
  - Fiber positioners
  - Spatial filters
  - Slits; pinholes
  - Newport 4x6 RS optical tables (2x)
  - Melles Griot 4x10 optical table
  - Shutters
  - Irises

- Sources
  - Red and green HeNe lasers (polarized)
  - Laser diodes (visible); laser diode supplies
  - Laser diodes (NIR)
  - UV sources
  - Xenon arc lamp
  - Halogen lamp

- Photonics Instrumentation
  - Photon Inc. beam profiler; asst'd heads
  - Pulnix CCD camera w/ fixed-focus, zoom, and telecentric lenses
  - ILX Lightwave optical multimeter
  - Newport optical multimeter with UV- and IR-extended detectors;boulometer
  - SRS optical chopper
  - Silicon, germanium, and InGaAs detectors; integrating spheres
  - High bandwidth and high dynamic range amplifiers
  - SRS low-noise current amplifiers
  - SRS low-noise voltage amplifiers
  - Collimation testers

- General-Purpose Instrumentation
  - Tektronix high-bandwidth digital storage oscilloscopes (2x)
  - Tektronix analog oscilloscope
  - Fluke hand-held oscilloscope
  - SRS spectrum analyzer
  - SRS dual-channel DSP lock-in amplifier
  - Kepco & AVC bipolar high-voltage power supplies
  - SRS 5kV power supplies
  - H-P function generators
  - H-P dual- and triple-output power supplies
  - Krohn-Hite high-bandwidth LP/HP/BP filter set
  - Krohn-Hite and Ithaco filters
  - Ithaco instrumentation amplifiers
  - PCB and LDS vibration test equipment
  - Techron and Hafler power amplifiers
  - Fluke hand-held multimeters
  - Fluke hand-held temperature multimeter and probes
  - H-P 4-$^1/_2$ digit multimeter
  - H-P counter
  - R/L/C substitution boxes
  - RS-232 cable tester
  - Isolation transformers
  - Pentium workstations w/ SCSI-2, GP-IB; A/D, D/A, digital I/O
  - Data Translation framegrabber
  - VCR; color monitor
  - Macintosh workstation w/ GP-IB
  - IBM RS/6000 workstation
  - LabVIEW s/w development systems (PC and Macintosh)

- Prototyping Equipment & Supplies
  - VWR vacuum oven
  - Fiber cleavers
  - VersaTech fiber optic polisher
  - Fiber inspection scopes (20x)
  - Fiber inspection scope (200x)
  - Sherline vertical milling machine
  - Sherline lathe
  - Drill press
  - Grinder
  - Sander
  - Shear press
  - Solder stations; electronics workbenches
  - Laminar flow hood
  - Fume hood
  - Electrical components and supplies

Mechanical components and supplies
Adhesives; encapsulants

3.3.1.2 Photonics Computer-Aided Design Facility

The Photonics Center CAD Lab is located adjacent to the Photonics Systems Engineering Lab on the 9th floor. The state-of-the-art computing hardware consists of a Sun UltraSparc 60 server and three Pentium II 400 MHz workstations. The Sun server currently hosts Code V, LightTools, BroadNeD, Mathematica, and Matlab, all available to clients via X-Windows. The Intel machines provide a cluster of high-speed 3D-graphic workstations and also host the BPM_CAD suite of waveguide optics modeling software. A high speed Tektronix thermal-wax based color printer serves all computers in the CAD Lab. The software tools provide analysis and synthesis of photonics components and systems and include:

<u>CODE V:</u> CODE V is ORA's comprehensive, industry-leading program for optical design, analysis, illumination calculations, and fabrication support. It is used by organizations around the world to design a wide range of optical systems for a variety of products, including photographic equipment, video cameras, medical instruments, and aerospace systems.

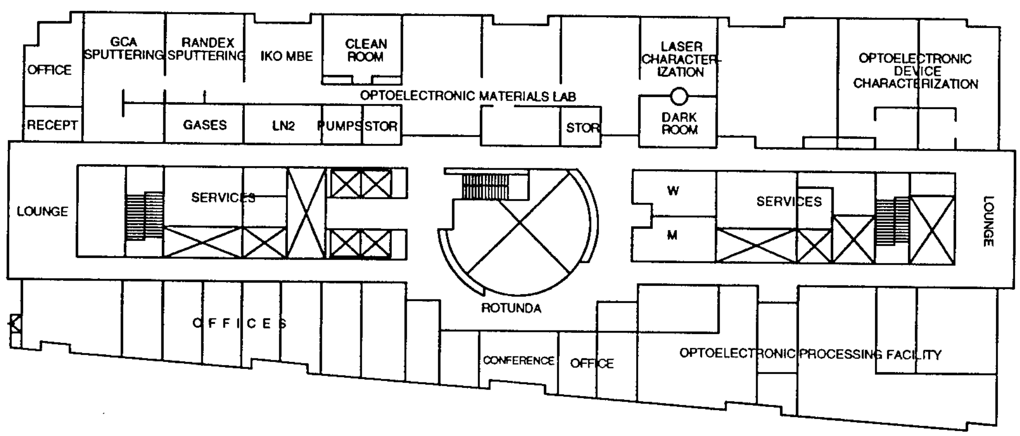
<u>LightTools:</u> LightTools complements Code V with 3D solid-based optical and opto-mechanical modeling. LightTools offers specialized optical and illumination analysis features and complete optical accuracy with a fully interactive graphical interface similar to modern mechanical CAD packages.

<u>BPM_CAD:</u> The BPM_CAD suite is a powerful, user-friendly package that allows computer-aided design of a variety of integrated and fiber optics guided wave problems. The beam propagation method, or BPM, is a step-by-step method of simulating the passage of light through any waveguiding medium. The software suite also includes IFO_Gratings, a design and analysis package for grating-assisted devices calculating light propagation, reflection and transmission spectra. WDM_Phasar provides tools based on phased arrays for design and modeling of Wavelength Division (De)Multiplexers (WDM) devices, key components optical telecommunication links and networks.

<u>B-NED:</u> BroadNeD is a powerful photonic network design package for WDM telecommunications, which fully addresses complicated physical effects such as accumulating nonlinearities. State-of-the-art fiber communication systems can be simulated with detailed performance analysis and optimization capabilities.

3.3.2 Eighth Floor

Critical to photonics applications are opto-electronic devices and components to generate, control and detect light. Optoelectronic devices such as semiconductor lasers and detectors have been the enabling technologies for a number of applications, including fiber optic communications, lower cost and high-reliable laser range finders, and affordable optical data storage. The eighth floor of the Photonics Center Building has been structured to provide the laboratory facilities and equipment for fabrication and test of optoelectronic devices and components. Fifteen different laboratory areas and clean rooms go into making up this capability which fall into three main functions: (1) growth of high quality semiconductor material used for optoelectronic devices, (2) processing of the material to form optoelectronic devices, and (3) characterization and testing of the finished devices.



8^{th} FLOOR

FIGURE 3.3

Photonics Center Building Eighth-Floor Layout

3.3.2.1 Optoelectronics Materials Laboratories

The Optoelectronics Materials Laboratory provides various modern methods of film deposition for the growth of materials and device structures for optoelectronics applications. Such methods include molecular beam epitaxy (MBE), vapor phase epitaxy (VPE), chemical vapor deposition (CVD), sputtering, and evaporation. The current program emphasized in this laboratory is in the area of wide band-gap semiconductors, which include III-V nitrides, and diamond thin films. These classes of materials are useful for various optoelectronic devices (LEDs, lasers, and detectors) operating in the visible and ultraviolet part of the electromagnetic spectrum. Furthermore, the same materials are useful for high temperature and high frequency electronic devices as well as electromechanical actuators and sensors.

Two MBE units are located in the Materials Laboratory, dedicated to the growth of III-V nitride materials and structures for optoelectronic devices. Both systems are configured to grow, on three-inch wafers, the entire family of III-V nitrides which includes the three binary systems (InN, GaN, AlN) as well as there ternary and quaternary alloys. Both systems are configured with ECR or RF plasma sources for activation of the nitrogen used in growth. Further, both systems are equipped with a number of *in situ* diagnostic tools to monitor the growth processes. The VPE system has been custom designed and fabricated by Photonics Center researchers for the growth of GaN thick films useful as substrates for subsequent MBE thin film growth as well as new techniques for the growth of low defect III-V nitride materials. The CVD system is ECR assisted and has been configured for the growth of diamond thin films as well as ECR-assisted reactive ion etching of III-V nitrides. The sputtering and evaporation systems are multi-targeted units capable of depositing both metallic and dielectric materials.

The laboratory is also equipped with a variety of characterization equipment including a Hall effect apparatus for measuring transport coefficient of III-V nitrides from 10K to 1000K, and a photoluminescence apparatus with CW HeCd and pulsed nitrogen lasers for measuring materials' luminescence properties from 10K to room temperature.

Major Equipment:

- Varian Molecular Beam Epitaxy Unit
- IKO Molecular Beam Epitaxy Unit
- ECR-Assisted Chemical Vapor Deposition Unit
- Vapor Phase Epitaxy Unit
- Perkin-Elmer Multi-Target Sputtering Unit
- E-Beam Multi-Target Evaporation Unit
- Class 100 Clean Room
- Class 10000 Clean Room
- Hall Effect Apparatus
- Photoluminescence Measurement Apparatus
- Suite of electronic and optical inspection test equipment

3.3.2.2 Optoelectronic Component Fabrication Facilities

The Optoelectronic Component Fabrication Facility is a multi-user facility used for prototyping optoelectronic devices such as LEDs, semiconductor lasers, photodetectors as well as other devices. The facility includes clean rooms as well as the necessary equipment for photolithography, wet chemical processing, thin film and metal deposition by thermal and e-beam evaporation, plasma etching and deposition, and packaging of finished devices. The facility is staffed by a full-time professional who assists in running fabrication processes, trains others in use of equipment, maintains the equipment, and assists our industrial partners in applying the capabilities of the Optoelectronic Component Fabrication Facility to their needs.

<u>Major Equipment:</u>

- Suss Mask Aligners (2)
- Reactive Ion Etch Systems
- Rapid Thermal Annealing Unit
- Dual e-beam, dual thermal evaporator
- Edwards Evaporators (2)
- Reactive Ion Beam Deposition System
- Plasma Enhanced Chemical Vapor Deposition System
- Denton RF Magnetron Sputtering System
- Probe Station
- Circuit Analyzer
- Class 100 Clean Room
- Class 1000 Clean Rooms (2)

3.3.2.3 Optoelectronic Devices Characterization Laboratories

The Optoelectronics Device Characterization Laboratory has been established to provide both optical and electrical testing of a wide variety of optoelectronic devices as well as materials characterization. For optical characterization, this includes emission efficiency, linewidth, purity, and the emission pattern, all of which ultimately determine the performance and value of a particular device for commercial applications. In addition to device characterization, materials characterization is of fundamental importance because the materials' properties directly influence device parameters. Materials characterization is performed with optical excitation of the material over the ultraviolet-visible-infrared bands (195 nm to 1.8 um). In addition, an array of other optical measurements can be performed including reflectivity, photo-reflectivity, absorption, optical pumped stimulated emission, and optically pumped lasing. These measurements can be performed at room temperature or a liquid nitrogen temperature (77K). The laboratory is also equipped for a range of electrical measurements that can be used to characterize materials or devices. Examples of these techniques include current-voltage, capacitance-voltage, and Hall effect measurements.

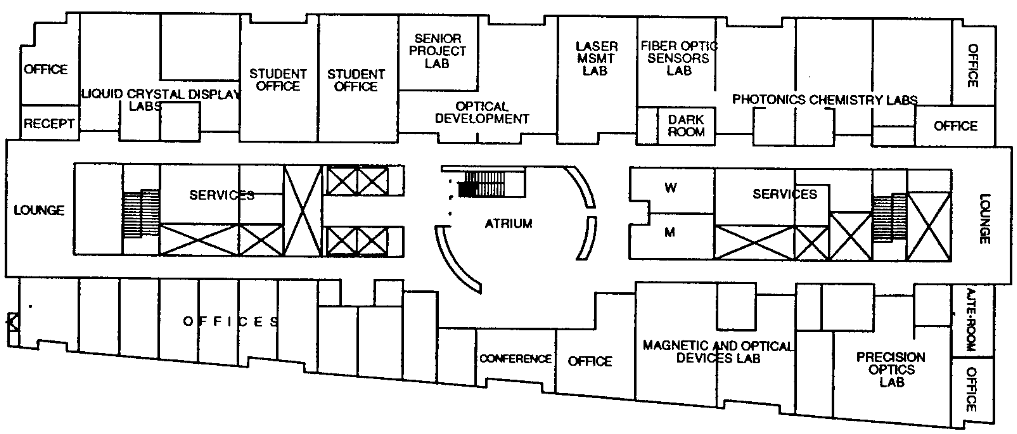
<u>Major Equipment:</u>

- AR laser
- HeNe laser
- HeCd Laser
- 9809 semiconductor laser
- Pulsed nitrogen laser

Spex 1 m spectrometer
Spex 75 cm spectrometer
Spec 20 cm spectrometer
Cooled Ge detector
GaAs photomultiplier
Si Detectors
UV enhanced UV detectors
Phase sensitive, frequency selective amplifier
Hall effect measurement apparatus
Stereo optical microscope
Nomarski optical microscope
Suite of standard electronic test equipment
Full complement of optical tables and optical components

3.3.3 Seventh Floor

The seventh floor of the Photonics Center Building provides the ability to support a variety of photonics technologies with wide ranging applications, including integration of MEMS devices for deformable mirrors, high-density magneto-optical data storage, improved flat-panel displays for large area displays, in-the-field chemical sensing, and new materials for dye lasers.



7th FLOOR

Figure 3-4
Photonics Center Building Seventh-Floor Layout

3.3.3.1 Photochemical Processes Laboratory

The Photochemical Processes Laboratory has been established for the investigation and new development of organic materials with applications to photonic systems and materials. In particular, this has included the development of new organic dyes with modified photocycles for use in dye lasers, non-fading dyes, and dyes with controllable time and wavelength fluorescence responses for a variety of applications requiring photochromic responses such as lenses for laser eye protection. Development of these new organic materials is dependent on controlling and characterizing the photochemical processes of the material, such as the time-resolved spectra and fluorescence polarization for emission measurements, the photochemical transients species that occur under illumination, and photolysis and actinometric measurements.

Major Equipment:

- FT nuclear magnetic resonance spectrometers
- Finnigan MAT-90 high resolution mass spectrometer
- Perkin-Elmer FT-IR spectrophotometer
- Chromatograph
- SLM 48000 S multiple frequency lifetime spectrometer
- Nd/YAG laser flash photolysis instrument
- Dye laser flash photolysis instrument
- Full suite of wet-chemistry equipment and supplies
- Varian XL400 Spectrometer (Shared equipment with Chemistry Dept)
- Unity 500 spectrometer (Shared equipment with Chemistry Dept)
- JEOL GSX270 spectrometer (Shared equipment with Chemistry Dept)

3.3.3.2 Liquid Crystal Display Laboratory

The Liquid Crystal Display (LCD) Laboratory is equipped for the design, simulation, fabrication, and characterization of LCD prototypes. Work in this facility is aimed at designing and fabricating LCDs with improved viewing angle and color rendition as well as advanced packaging approaches to improve display area. An important part of the facility is unique computer-aided-design software that has been developed by researchers at the Center for rapid simulation of color viewing angle characteristics of LCDs for angles ranging from 0 to 75 degrees, at various design voltages, and for various manufacturing parameters. Based on design and manufacture parameters developed using this unique simulation and modeling capability, LCDs are fabricated in the facility and then characterized using a unique instrument, termed a Fourier Scope, developed at the Center. The Fourier Scope permits the measurement of color viewing angle patterns in real-time. This unique instrument, which is based on principles of Fourier optics, alleviates the need for slow scanning systems and is more accurate than the conventionally used conoscopic systems. These novel CAD and characterization tools facilitate the development of innovative designs for new LCD structures.

Major Equipment:

- LCD rubbing machine

Spinner
Spacer deposition box
VacPac vacuum packaging system
Ultrasonic cleaner
Vacuum nitrogen oven
UV curing systems
Fourier Scope (for LCD characterization)
Custom CAD package (for simulation of LCD under various manufacturing parameters)
Full complement of LCD fabrication materials
Suite of standard electronic test equipment

3.3.3.3 Magnetic and Optical Devices Laboratory

The Magnetic and Optical Devices Laboratory is supporting developments of patterned magneto-optic memories, magneto-optic devices, and vertical Bloch line memories. The facility provides for the deposition of magneto-optic thin films such as TbFeCo deposited by sputtering in the Optoelectronics Components Fabrication Facility. Characterization is performed with a Kerr-effect loop tracer to determine bulk coercivity and Kerr rotation angle. In addition, several optical characterization approaches are available, including a microscope mounted Photometerics digital camera to measure broad area Kerr contrast and a Hammamatsu image processing system to capture and enhance images of materials and devices under investigation.

Major Equipment:

Olympus Microscope with Photometrics digital camera
Hammamatsu Image Processing System
Laser Stroboscopic Microscopic System
Kerr-effect Microscope

3.3.3.4 Precision Optics Laboratory

The Precision Optics Laboratory is equipped to address a variety of processes for precise grinding, polishing, lapping, and ion-machining for the fabrication of optical components as well as the necessary measurement equipment to characterize the surface quality of fabricated components for such parameters as smoothness and roughness. For ion-machining specifically, new techniques have been developed for definition of large and ultra-fine features on a diverse set of surfaces, including ceramic and metals, through use of a neutral ion beam. Work by Precision Optics Laboratory researchers has assisted a variety of commercial clients in the developments of new products such as advanced manufacturing methods for hard disk surfaces, precise mirrors structures, new manufacturing methods for compact discs and digital versatile discs, and adaptable mirror surfaces for wavefront control of optical communications laser systems.

Major Equipment:

- IBM Ultraprecision Diamond Grinding Machine
- Ion-Machining systems
- Nomarski Interference contrast optical microscope
- Zygo DMI-1000 Dynamic Measurements Interferometer
- Physical Acoustic emission measurement system
- Capacitive displacement gauging system
- Inductive displacement measurement gauging system
- Clean room with photo resist deposition equipment
- Suite of electronics test equipment

3.3.3.5 Laser Measurement and Fiber Optic Sensors Laboratory

The Laser Measurement and Fiber Optic Sensor Laboratory has been established to provide facilities for the development of field-portable, fiber optics-based spectroscopy systems for measuring and monitoring various contaminants in solution. Absorption, scattering, and Raman spectroscopy approaches have all been addressed to determine specific contaminants in solution, such as the presence of pesticides or chemical warfare agents in drinking water and the presence of marking dyes in fuel products. This facility has been configured to provide both the basic scientific measurements that establish the spectroscopic measurements needed to identify specific contaminants as well as the ability to prototype and test field portable spectroscopy units that have been transferred to an industrial partner for manufacture and sale.

Major Equipment:

- Kaiser Raman Spectrometer
- Spex Raman Spectrometer
- Assorted Fiber optic probes
- Raman 2000 spectrometers
- Assorted lasers (near IR and Mid IR)
- Optical power meters
- Suite of electronic test equipment

3.3.4 Sixth Floor

The sixth floor of the Photonics Center Building was programmed to provide business incubator space. At present the sixth floor is shell space, with the intention of bringing this portion of the facility on-line in the near future. This floor will provide a 23,500 sq. ft. multiple-use, small business incubator environment that accelerates the growth of start-up and expanding businesses in the photonics industry.

3.3.5 Basement

Due to the concrete mat used to isolate the structure of Photonics Center Building from the surrounding area, the basement of the Center has the lowest vibration levels of any building on the Boston University campus, and as such is ideal for locating laboratories that require precise optical measurements. In addition to the optical laboratories, the basement area contains facilities for preparing de-ionized water used throughout the building as needed, facilities for heating, and an electrical sub-station as required by code.

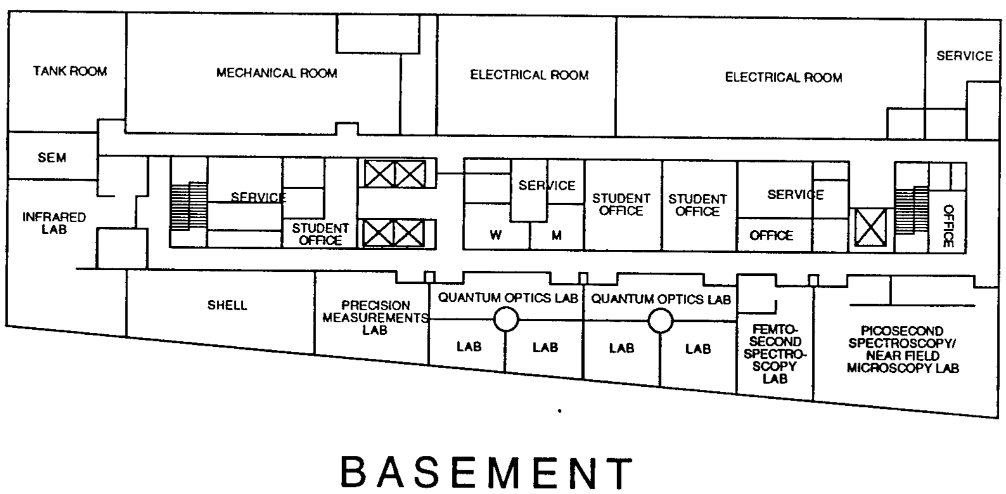


Figure 3-5

Photonics Center Building Basement Layout

3.3.5.1 Precision Measurement (SEM/AFM) Laboratory

The Precision Measurement Laboratory is a multi-user facility containing a scanning electron microscope and an atomic force microscope for precision surface analysis that is utilized by both Photonics Center researchers and our industrial partners. The facility includes a JEOL JSM-6100 Scanning Electron Microscope with a Kevex Energy Dispersive X-ray Spectrometer. The scanning electron microscope can image up to 300,000X with excellent depth of field and is an instrument of choice for viewing detailed topography of samples. The x-ray spectrometer provides information on the elemental composition of samples as small as 1 micron and has been equipped to provide quantitative analysis of light and heavy elements to 1% wt or below, depending on the individual element and its matrix. Also located within the Precision Measurements Laboratory is a DI-3000 Atomic Force Microscope (AFM) for the non-destructive surface analysis of conductive or non-conductive samples, samples in liquid, and biomaterial samples, at room temperature. Using both tapping and contact techniques, the AFM provides digital 3-D images of sample surfaces at near atomic levels. It also offers extensive analysis of surface roughness, section profile, and angular measurement of surface features. In addition, the instrument is capable of imaging using magnetic force measurements (MFM), electric force measurements (EFM), and scanning thermal measurements (SThM) for more advanced applications.

The laboratory is staffed by a full-time member of the Center Staff who performs analyses, trains others in use of equipment, maintains the equipment, and assists our industrial partners in applying the capabilities of the facility to their needs.

Major equipment:

- JEOL JSM-6100 Scanning Electron Microscope
- Kevex Energy Dispersive X-ray Spectrometer
- Nanoscope DI-3000 Atomic Force Microscope
- Sample preparation materials and facilities

3.3.5.2 Scanning Infrared Near-Field Microscopy Laboratory

Infrared spectroscopy is one of the most sensitive techniques for characterizing molecules that exhibit intrinsic vibrational modes. This is because the vibrational spectrum of a molecule can often serve as a unique identifying fingerprint. Because this form of vibration spectroscopy relies on the intrinsic normal modes of molecules, images are obtained without requiring the use of fluorescent or colorimetric stains, and the technique is non-destructive.

Scanning near-field infrared microscopy is a new technique that has been developed for combining infrared spectroscopy with high resolution spatial imaging below the diffraction limit, for a non-destructive characterization of micron sized particles. The new microscope is being utilized in a wide variety of applications of interest to bio-photonics, optoelectronic, biomedical, and semiconductor fields.

Major Equipment:

- CO gas laser
- Tunable OPO+OPA/DFG laser source
- Broadband infrared source
- Solid state (CW green) laser
- Tunable femtosecond visible -to-NIR Ti:sapphire laser
- Infrared optics
- Cryogenic infrared detectors
- Infrared focal plane array
- Infrared microscope
- IR linear array detector
- IR and visible monochrometer
- Visible microscope with CCD camera
- Suite of standard electronic test equipment
- Full complement of optical tables and optical components

3.3.5.3 Femtosecond Laser Facility

The ability to probe and ultimately control the responses of materials on the fundamental time scale of atomic/molecular motions is central to the design and characterization of optoelectronic materials and devices. The Femtosecond Laser Facility has been established to provide these fundamental measurements. This facility is equipped to perform optical measurements over the near UV to IR range with pulses of less than 50 femtoseconds and a high repetition rate of the amplified laser system. The Femtosecond Laser Facility provides the capability of directly observing the time scale of nuclear motions and the evaluation of ultrafast electronic and optoelectronic properties of a variety of photonic materials. The Facility represents an increasingly important tool for the development and characterization of a diverse range of photonic materials and devices, including novel semiconductors, biomaterials, and organic and inorganic molecular systems used for photonic applications.

Major Equipment:

- Coherent Mira seed Ti:sapphire laser
- Coherent Saber Ar-ion laser
- Coherent Ti:sapphire regenerative amplifier
- Coherent Optical Parametric Amplifier
- Femtosecond Real-time Autocorrelator
- Full complement of optical tables and optical components
- 1/4 m Spex monochrometer
- Suite of standard electronic test equipment

3.3.5.4 Near-Field Scanning Microscopy Laboratory

The Near-Field Scanning Optical Microscopy (NSOM) facility has been established for ultra-high resolution microscopy and spectroscopy using near-field optical techniques. Present capabilities include super resolution imaging of materials and devices in the spectral range from the near ultraviolet to the mid infrared. NSOM is a recent technique where a tapered single-mode optical fiber probe is placed within a fraction of a wavelength of a sample and scanned over the surface. Because both the tip-to-samples separation and the tip aperture are a small fraction of the wavelength, the spatial resolution for the scanned optical microscopic systems is given approximately by the tip diameter. Resolution as much as 20 times better than the best conventional microscope can be obtained. High-resolution characterization of materials and devices is performed by collecting emitted light in the near-field or by local photo-excitation of an optically active material with light from the optical fiber tip. For example, using wavelength tunable sources, near-field optical beam induced current measurements can provide information on the compositional and electronic structure of semiconductors and biomaterials. NSOM can also be used to study the evanescent field of waveguides and couplers, the temperature profile of active devices, and various combinations of local excitation and collection of light.

Major Equipment:

- Burleigh Wavemeter
- Conoptics Pulse Picker
- Dye laser
- Femtochrome Autocorrelator
- General purpose NSOM
- ISA HR640 Monochrometer
- Low-temperature NSOM
- Princeton Instruments CCD11000-PB UVA
- Ring Laser operating at 1.3 microns
- Spectra Physics CW Ti:Sapphire laser
- Spectra Physics Millenia V laser
- Waveguide NSOM

3.3.5.5 Picosecond Spectroscopy Laboratory

The Picosecond Spectroscopy Laboratory provides excitation sources, spectrometers, and detectors for the investigation of linear and non-linear optical properties of materials and devices by providing time-resolved measurements at the picosecond level. The facility is providing support for a number of investigations including: (1) determination of second harmonic generation in III-V optical waveguides for blue and UV laser sources, (2) time resolved characterization of photodetectors operating at wavelengths from UV to near-IR, (3) time-resolved near field optical characterization, and (4) optical characterization of GaN thin films, among others.

Major Equipment:

- Ar-Ion Laser
- Ti: Sapphire laser
- Non-linear Harmonic Generator
- Probe Station with microwave probes
- Semiconductor parameter analyzer
- Suite of standard electronic test equipment
- Full complement of optical tables and optical components

4.0 Photonics Center R&D Projects

Several technology development programs were undertaken at the Center under this Grant. These projects cover a broad range of photonics technology areas, including optoelectronic materials and devices, portable spectroscopy, advanced instrumentation, near-field optics, quantum optics, LCD modeling and fabrication, biophotonics instrumentation, fast dyes, and magneto-optic materials and devices, among others. Brief descriptions of these projects are presented below.

4.1 Materials and Devices

4.1.1 Fluorescent Markers for Medical Testing

An exciting potential for growth in the separations industry in general and the electrophoresis arena specifically is the development of high sensitivity, luminescent detection systems for specific classes of proteins that obviate the need for radioactivity. The goals of this R&D program are to develop luminescent systems for the detection of biologically significant classes of proteins separated by electrophoretic techniques. A luminescent protein stain is expected to offer the sensitivity of radiolabeling, without the accompanying inconveniences and risks. This project focuses on developing readily reversible, luminescent probes that are suitable alternatives to 141C, 35S, 32P and 33p labeling of proteins in biological materials.

Many bioanalytical assays have gravitated from the use of radioactive labels to nonisotopic detection systems. The hazards of working with radioactivity as well as its limited shelf-life have motivated this change. Popular alternatives to radioactivity are colorimetric, chemiluminescent, or fluorescent detection. Certain metal complexes selectively interact with proteins immobilized on membrane supports to form brightly colored products. The metal complexes bind proteins at acidic pH but are eluted from the proteins by basic pH solutions that contain other chelating agents. The reversibility of the protein staining procedure allows for subsequent biochemical analyses (immunoblotting, protein sequencing, mass spectrometry).

Measurement of light absorbance is an intrinsically insensitive method since it is limited by the molar extinction coefficient of the colored product. Measurement of light emission is theoretically more sensitive but conventional fluorescence detection methods suffer from difficulty in discriminating between signal and nonspecific background, especially in biological samples. Better discrimination of signal from noise can be achieved if the fluorophore has a large Stoke's shift and a long emission lifetime.

We have developed luminescent lanthanide chelates that have large Stoke's shifts (250-3350 nm), long emission lifetimes (100 us-1 ms), and relatively narrow-band emission (1-20 nm). These fluorophores can be observed with inexpensive pulsed-excitation time-gated detectors. Only the desired signal is measured since short-lived background emission is allowed to decay before data recording begins. Since the fluorophore has narrow-band emission, filters can be employed for improved discrimination of signal.

4.1.2 Ultra-Lightfast Organic Dyes

Organic dyestuffs comprise an enormous range of commercial applications. High volume dyes fulfill fundamental roles of providing color or brightening in textiles, printing, and other photoimaging systems. More specialized applications that are emerging for organic dyes have to do with non-linear optical properties (e.g., optical modulators or waveguides), integrated optics, liquid crystal or electroluminescent displays, and bioanalytical science (e.g., fluorescence probes). For most of these applications, the fading of dyes that have been impregnated in a solid matrix is a critical factor in limiting the performance of materials or devices. Virtually all classes of dyes (e.g., xanthenes, triarylmethanes, cyanines, azos and anthraquinones) are subject to some form of light-induced degradation. The mechanisms of photochemical reaction are diverse and include the formation of long-lived reactive chemical intermediates such dye triplet states and free radicals. Reactions associated with photochemical instability also involve interaction of dye with dissolved oxygen, polymer materials, and additives in the matrix.

Research currently underway at the Photonics Center is directed to establishment of a new paradigm for the construction of ultra-stable dyestuffs. The basic tenet holds that dye chromophores can be modified judiciously so that a single benign photochemical mechanism will predominate over all others. The mechanism of choice will be one that can be applied, in principle, to any class of dye structure. The concept involves the design of dye structures that have been modified with groups that engage in reversible electron transfer with the primary dye chromophore. According to this design, dyes will have a "short circuit" built in that insures that photoexcited species return to the ground state on the shortest possible time scales and with exceptional fidelity. With appropriate modifications in dye derivatives, processes that normally compete in excited state decay, such as fluorescence, intersystem crossing to give dye triplet states, or atom abstraction involving the matrix are virtually completely suppressed.

Investigations of the new family of organic dyes having exceptional light stability is proceeding with a variety of sophisticated mechanistic probes. These studies include measurement of phtotransients of the radical or radical-tion type appear on very fast time scales. Using pump-probe methodology that is appropriate for both femtosecond to nanosecond and nanosecond to millisecond time domains, the fate of dyes with respect to discrete photochemical steps can be assessed in great detail. With this critical resolution of competing chemical relaxation phenomena, degradative pathways that lead to dye photofading will be more thoroughly understood and strategies for their elimination established.

4.1.3 Scintillator Crystal Development

This project focused on the development of new high-output, fast scintillator crystals based upon LuAlO3. 2-inch crystals of LuAlO3 doped with Ce were grown. These crystals proved to be colorless, indicating the absence of major impurity or color center, and to have high optical homogeneity and clarity. The nominal Ce doping of the first crystal was 0.25%, and a second crystal was doped with 0.75%.

Detailed evaluations of the crystals showed that the theoretical density of 8.4g/cm3 was achieved, indicating that the material is indeed the Lu aluminate. Under both optical and gamma ray excitation the crystals showed Ce emission at 370nm. The scintillation decay time was measured at

18ns. Light output of up to 32,000 photons per MeV -- 4 times that of BGO or 85% of NaI:T1 -- was measured in crystal 2. These parameters indicate that the new crystals are among the best scintillators reported to date.

4.1.4 Bacteriorhodopsin (bR) For Document Security

Counterfeiting of consumer products, official documents, currenty, etc. is a world-wide problem. Security and authentication methods employed to date have focused on the "casual" counterfeiter, concentrating on means designed to thwart present-day copy machine and scanner technology applied to counterfeiting. A new method of surface marking has been developed using the biological material bacteriorhodopsin (bR) and its mutants.

In practice, bR is affixed to an item to be protected against counterfeiting either directly, on a substrate attached by a label, or embedded in a matrix attached by a label. When stimulated by the appropriate wavelength and intensity of light, the bR undergoes a unique and identifiable photocycle in which the light absorption properties of the bR follows a specified dynamic pattern which can be visually or electro-optically detected to verify authenticity of the item. In this proejct, bR has been developed and deposited as text and graphic printing, which is nominally purple in color. The bR marking has been programmed to "wash out" during copying (photocopying, or computer scanning), and to copy directly in the purple color. To authenticate the item, the known photocycle is triggered by a stimulus light source, and the "correct" photocycle is then sought. If found, the item is authentic; if not, the item is counterfeit. Most importantly, depending on the mutant used, the photocycle may be manually triggered and visually observed for point-of-sale or point-of-process application, or may be machine triggered and automatically detected for high speed authentication of documents.

4.1.5 Magneto-Optic Materials and Devices

During the microscopic study of magnetic thin films for erasable optical storage, it was observed that local magnetic coercivity (the field H, at which reversal occurs) changed with mechanical roughness or film stress. Initially this was viewed as a problem, because it contributed media noise, and substrates were polished and cleaned to lessen the effect. Later, it was realized that controlling the local coercivity might allow precise positioning of data marks and reduce the laser power needed to write.

Boston University's Photonics Center is supporting research in the Magnetic and Optical Devices Laboratory to create and characterize patterned magnetic thin films. Projects have been undertaken in patterned magneto-optical media and vertical Bloch line memories, both of which exploit patterning of thin magnetic films to control local micromagnetics.

4.1.6 Patterned Magneto-optical Media

Magneto-optical erasable storage media have a thin (900 nm) amorphous TbFeCo active layer in an optical stack. Media are stamped with a spiral track and marks are written on the land areas by laser heating in a bias field of about 100 Oe. Mark widths, determined by the laser isotherms, are about 0.6 um. Readout is by Kerr effect readout, i.e., the two magnetic states produce different rotations of the read beam's polarization.

Our research consists of three efforts: development of patterned sample substrates: deposition of magneto-optical thin films and characterization of the micromagnetics and data mark behavior. Substrates are masked with a variety of structures and machined using ion milling facilities. We also have access to Si and fused silica CD masters and to PPMA CD blanks. TbFeCo thin films are deposited by DC planar magnetron sputtering in our Denton Vacuum Discovery 18. Passivation layers of SiN or AlN can be deposited, and an Al layer can be added for thermal conductivity.

Characterization with a standard Kerr-effect loop tracer yields bulk coercivity and Kerr rotation angle. A Photometrics digital camera, mounted on a modified Olympus microscope, gives broad area Kerr contrast microscopy of our samples. The microscope has a substage electromagnet to nucleate domains, and an 830nm laser diode that can focus on the sample through the objective, to allow thermally-induced nucleation.

Our experimental work in patterning magneto-optical films is supported by simulations of the patterned surface as part of the optical read/write system. These simulations recently confirmed that patterned substrates should not adversely affect the tracking and focusing servos of a typical magneto-optical storage drive.

4.1.7 Vertical Bloch Line Memories

Honeywell and the Jet Propulsion Lab are developing ultra-high-density solid state memories based on the twists in the wall structure surrounding a thin-film magnetic domain. Our laboratory supports the effort with modeling of the micromechanics of Bloch lines on the Power Challenge Array supercomputer, and by optically characterizing the wall structures with a laser stroboscopic microscope and image processing.

Garnet thin films are etched to form elongated oval raceways. Magnetic domains nucleated within the raceways are stable and can maintain VBL twists created by an electronic 'write' structure. VBL twists can be recovered at an electronic 'read' structure. The key phenomenon is the stabilization and control of magnetic domains in the thin film by patterning. The laser stroboscopic microscope illuminates the Honeywell devices with synchronized dye laser pulses. The Faraday effect is used to image the domains in the garnet. The applied magnetic field is also varied to allow measurement of key device parameters, including wall velocity and acceleration, from which VBL twists can be inferred (they are too small to observe under visible light). A Hammamatsu image processing system is used to capture and enhance multiple images, providing improved measurements of VBL properties.

4.1.8 III-V Nitride Materials

The family of III-V nitrides is the most promising class of Optoelectronic materials. The three binaries (InN, GaN, AlN) together with their alloys span the spectrum region form 1.95eV to 6.28eV, therefore making them suitable for optical devices (LEDs, lasers, detectors) operating in the visible and ultraviolet part of the electromagnetic spectrum. The same materials are also suitable for the fabrication of devices for high-temperature, high-frequency and high-power electronics. The unique physical properties of these materials also make them suitable for piezo-electric, opto-electronic, and acousto-optic devices.

Research projects in the III-V materials address both material and device issues of the family of III-V nitrides grown by MBE and hybrid VPE methods. These studies cover both bulk thin films as well as heterojunctions and multiquantum wells. Material issues include growth and doping of III-

V nitrides by plasma-assisted MBE. Particular emphasis is placed on developing the InGaN alloys for optical devices operating in the visible spectrum. Issues related to miscibility of the InN-GaN pseudobinary system are being addressed. The AlGaN alloy system is also being optimized for applications in the ultraviolet part of the spectrum.

The device program includes the fabrication of blue-green LEDs and lasers and solar-bind ultraviolet detectors. These programs are funded by ARPA in various industrial consortia.

4.1.9 III-V Nitride Devices

The Boston University Photonics Center has established a new optoelectronic device prototyping laboratory which includes state of the art photolithographic patterning, wet chemical processing, thin film deposition by thermal and electron beam evaporation, plasma etching and deposition, ion beam deposition, and other processing equipment. The processing facility is complemented by a semiconductor device characterization laboratory for the assessment of device characteristics, including photoluminescence, reflectivity, photoreflectivity, absorption, optically pumped stimulated emission, optically pumped lasing, current-voltage, capacitance-voltage, Hall effect, light-versus-current, farfield pattern, and radiative efficiency. The measurements can be performed at room temperature and 77 K. The examples below describe the device development conducted in the area of optoelectronic devices.

4.1.9.1 Microcavity Devices

Resonant cavity light-emitting diodes (RCLEDs) are a new generation of light-emitting diodes (LEDs) which can emit ten times higher intensities than LEDs manufactured at the present time. These diodes consist of microscopic optical resonators with a distance between the two reflectors equal to just a fraction of the wavelength of light emitted by the device. A light-emitting active region is located between the two reflectors. Resonant microcavities strongly enhance the spontaneous emission from an active region. Whereas microcavities were demonstrated in the GaAs material system a few years ago, only recently has the first demonstration of enhanced spontaneous emission been demonstrated at Boston University.

4.1.9.2 Lasers and Light Emitting Diodes

Short wavelength semiconductor lasers and LEDs emitting in the visible and the ultraviolet part of the optical spectrum have many applications, including flat panel displays, the next generation of very high density optical data storage, and novel light sources capable of replacing inefficient incandescent sources. Our efforts are directed towards the realization of device prototypes by manufacturable processes. Recently, stimulated emission in III-V nitrides has been demonstrated in our laboratory. A new method for facet fabrication yielding a facet roughness of 50 A has been developed. The roughness meets the requirements for high-efficiency operation of semiconductor lasers.

4.1.9.3 Materials Development and Characterization

The device fabrication is complemented by materials characterization and development. The focus of our work is on low-resistance ohmic contacts and high conductivity materials. Bandgap engineered structures have been employed to increase the conductivity of materials with deep impurities. Simulations show that the conductivity of materials can be increased by more than one order of magnitude.

4.2 Components

4.2.1 Bi-Linear Charge-Coupled Device (CCD)

A bi-linear CCD array has been developed which may be employed to locate the centroid of a charge cloud produced by microchannel plate stacks. The anode comprises a checkerboard-like structure of x- and y-conductive pads. The x-pads are connected in columns and feed charge into x-charge buckets via a FET pass gate. The y-pads are connected rows, and similarly feed charge into y-charge buckets. A conductive area collects the charge that misses the x- or y- pads, and is used to sense the arrival of a charge cloud. The x- and y-charge buckets, under the influence of x- and y-shift circuitry, pass their charge to x- and y-charge amplifiers. X- and y- counters keep track of the number of x- and y- shifts that occur before x- and y- detectors, and locate the x- and y- bucket containing the most charge. Latching the x- and y-counter values when the respective x- and y-peaks occur captures the centroid coordinates of the charge cloud.

This device may be employed to correct distortions in scintillation camers, which are used for imaging high-energy photons emitted from nuclear processes (gamma rays).

4.2.2 LCD Development

Research in the Liquid Crystal Display (LCD) laboratory aims at designing and fabricating prototypes of LCD devices with improved viewing angle characteristics and enhanced color rendition. The lab is equipped with CAD software for the rapid simulation of color viewing angle characteristics as functions of the applied voltage, and for various design parameters. It is also equipped with a home-invented instrument called the Fourier Scope, which measures the color viewing angle patterns of LCDs in real time for angles up to 75 degrees. These CAD and characterization tools facilitate the development of innovative designs for new LCD structures.

Prototypes developed in the LCD Lab include a single-polarizer reflective nematic LCD in a retarder compensated parallel-alignment configuration with appropriate parameters determined by use of the CAD system. The device is used to make reflective color displays with wide angles of view in the horizontal and vertical directions. The use of single-polarizer reflective nematic LCDs is of interest because of the desire to reduce power consumption and to enhance the reflectance above that of two-polarizer reflective LCDs and to eliminate parallax. Cells with 90, 63.6, or 240 degree twist angles have been reported in the literature. The off-normal viewing characteristics of such cells, however, have not been adequately investigated.

The viewing-angle characteristics of several single-polarizer reflective LCDs developed in the LCD Laboratory were recently determined by using computer simulations and by experimental observations on home-fabricated prototypes. It was found that using appropriate parameters, the film-compensated parallel-alignment configuration LCD can provide a rather homogeneous grayscales over a wide viewing-angle range. Since in a color LCD, different colors are realized by combining different colors R, G and B subpixels, the wide viewing-angle range for all grayscales implies a wide viewing-angle range for full-color direct-view LCDs. The computed and measured viewing angle results are then plotted in the form of true-color pattern arrays as well as conventional electro-optical curves and contours. A set of such patterns is determined for various values of the optical birefringence parameter of the liquid crystal cell. A systematic study of this and other effects is conducted as part of the design process. Animation of the color-pattern arrays is also used to include the effect of additional parameters. This enables a systematic search in a 3- or 4- dimensional parameter space.

In the particular case of a single-polarizer LCD cell, the result of the parameter study led to the selection of a single-polarizer reflective LCD consisting of a polarizer, a retardation film (RF), a liquid-crystal cell with parallel alignment (no twist), and a reflector which could be the rear reflective electrode. The birefringent optical path difference of the liquid-crystal cell is equal to the retardation of the retardation film. The optical axis of the retardation film is perpendicular to the molecular director of the liquid crystal, and makes a 45 degree angle with the polarizer axis. This leads to a normally-white mode. It is important to select the path difference in the range from 150 nm to 200 nm in order to obtain a wide viewing-angle range for all grayscales. Within this range, larger path differences give higher modulation sensitivity, but smaller path differences provide smoother grayscale viewing-angle distributions. By selecting a retardation film with smaller dispersion than the liquid crystal, almost achromatic performance can be achieved. These predictions have been verified on prototypes fabricated in this laboratory.

Conventionally, the regular active-matrix, or passive-matrix, addressing techniques are directly transplanted from the transmissive LCD technology to the reflective LCDs. As a result, limitations such as the maximum panel size and the pixel number for the active-matrix or the maximum row number for the passive-matrix, will also apply to the reflective LCDs. Since in the single polarizer reflective LCDs, metal reflective electrodes are usually used instead of transparent ITO electrodes on the rear substrate, and since the rear substrate is not an optical path, the rear substrate can provide a third dimension for accessing electrode terminals. An electrode-through-substrate (ETS) addressing method is being pursued in this laboratory. Technologies such as tape-on-substrate or chip-on-substrate are considered. The transparent electrodes at the front substrate are patterned as row electrodes if each segment at the rear substrate covers more than one row. In the limiting case when each segment corresponds to one row, a single uniform front electrode can be used.

This new ETS method could provide the following potential advantages: 1) Unlimited numbers of addressable rows (because all segments are addressed simultaneously and independently, and are therefore suitable for high definition displays such as super VGA or high-definition TVs. 2) Increased duty cycle of the applied voltage, and therefore better display quality, is achieved without the need of thin-film-transistor (TFT) technology. This could lead to a breakthrough in the pixel number, which is currently limited by the TFT technology. 3) Because the TFT process in AMLCD is replaced here by relatively inexpensive substitutes such as thick film or printed circuit technologies, the manufacturing cost could be much lower.

4.2.3 Optical Processing Facility

An Optical Processing Facility was established to facilitate device processing and fabrication test capabilities for use with GaN/AlN and GaAs/AlGaAs optoelectronic devices, nanopatterns for nearfield scanning optical microscopy, and education of graduate students. The facility includes electron and optical micriscopes, conventional and deep-UV-flood photolithography, thermal and dual-e-beam, evaporators, plasma etching, a precision mask aligner with near-UV capability, a modern reactive ion etching system, probe stations for electrical and optical testing of unpackaged devices, and a semiconductor parameter analyzer.

4.2.4 Polarization Sensitive Photodetectors

Present photodetectors detect the presence of light alone, but provide no indication of the light's polarization. Polarization is most typically sensed by splitting the incident beam into two light paths, consisting of the TM and TM polarization components, and passing them to conventional detectors, the outputs of which are compared to yield polarization. The use of bulk discrete optical components of this type requires indidual alignment in three spatial and three angular coordinates, resulting in high manufacturing cost and limited range of application.

The detector developed here is based on resonant cavity enhanced (RCE) photodetectors. The RCE structure consists of a thin absorption region placed in an asymmetric Fabry-Perot cavity. The cavity is formed by top and bottom reflectors which may be fabricated by alternating layers of quarter-wavelength dielectrics, e.g., a distributed Bragg Reflector. The optical length of the cavity satisfies the resonance condition, the cavity enhances the optical fields, and the detector response is drastically increased. For off-normal incidence of light, the reflectivity of a semiconductor/air interface may be significantly different for TE and TM polarizations. At Brewster's angle, for example, TM reflectivity vanishes and TE reflectivity is approximately 75% (for GaAs). Therefore, sensitivity, e.g., quantum efficiency, is a strong function of the cavity length for TE polarization while sensitivity for TM is invariant.

The device consists of a pair of monolithically integrated RCE photodetectors with cavity lengths tuned for resonance and anti-resonance for TE polarization, providing a high contrast. A comparison of the current from these two detectors under equal illumination yields the absolute polarization of the incident light. No bulk optics are required, and consequently, no complex alignment.

4.2.5 MEMS Scanners

The bimorph scanner consists of two flat strips of material joined over their long surfaces, cantilevered at one end. These strips expand or contract differently under the application of an external electric field, causing the bimorph to bend. By attaching a mirror to the end of the bimorph, this bending is used to deflect a beam of light. For example, the bimorph may be used to direct the beam of a laser for barcode scanning.

The bimorph developed here was originally created as a micromechanical piezoelectric bimorph actuator. However, when the bimorph was built, it was discovered that the expansion of the zinc oxide layer due to ohmic heating was much greater than the associated piezoelectric expansion, yielding a much larger deflection for the same applied voltage. Also, since the response is essentially thermal, the bimorph always bends in the same direction independent of the direction of the applied voltage.

The bimorph consists of a sandwich of metal-zinc oxide-metal deposited on a silicon substrate. The structure is etched to create a beam fastened to the substrate at one end, and a metal mirror is deposited at the free end. When a voltage is applied to the two metal coatings, an electric field is created in the zinc oxide piezoelectric, which expands differentially from the silicon, causing the bimorph to bend. The resulting angular rotation of the free end can be used to deflect a light beam through double this rotation angle. Angular rotations as large as 60 degrees were obtained from 7mm long bimorphs for voltages in the 60-100V range.

4.3 Systems

4.3.1 Portable Spectroscopy

An optical sensor was developed to spectroscopically differentiate the presence of organic contaminants in aqueous environments. Targeted contanimants are of the organiphosphorus class, a series of chemical species that is the structural basis for a wide variety of contaminants found as pollutants in water sources, including pesticides such as malathion and parathion. Surface-enhanced Raman spectroscopy (SERS) was employed to evaluate water effluent.

A prototype laser diode-pumped fiberoptic system was developed. The system is small, compact, portable, and field reliable and can be configured for direct reporting or automated remote operation. It incorporates a diode laser interfaced to an optical fiber bundle which both transmits the laser light as the scattering source and collects the light scattered back at the fiber tip. The scattered light is returned to a dispersion element (grating or filter) and a solid state diode detection array. The fiberoptic probe is immersed in a water source and the contaminants are detected as they diffuse into the sample compartment at the end of the fiber bundle. The scattered light signal is then carried by fiberoptics to the spectrometer at a convenient distance from the sample setup. A microprocessor was incorporated to report the appearance of any selected contaminant signal.

Two Raman spectra of parathion were run in a series of experiments. First, the pure material was run as a (neat) powder without any SERS. This spectrum was used to identify the important Raman features to allow identification of the molecule in water. The strong Raman spectrum is dominated by the modes around 1350 cm-1. Following experiments on the neat material, the

SERS systems was employed in liquid phase measurements. Strong Raman features were noted with concentrations in the parts per billion range.

4.3.2 Femtosecond Laser Facility

Ultrafast femtosecond lasers provide a tool for directly measuring in the time domain the material responses approaching the theoretical limits set by nature. The short time measurements of transient optical phenomena are essential to the characterization of photonic materials. Recent advances in ultrafast lasers allow the direct time probing of material responses on times scales as short as 20 femtoseconds (fs). Additionally, the high intensities achievable with these ultrafast optical pulses makes them an ideal tool for the measurement of nonlinear optical properties.

A femtosecond laser facility was established to provide the means to measure material responses and characteristics in the terahartz region of novel photonic materials developed at Boston University, and as a laboratory for the development of optical techniques for the control and manipulation of material reponses via ultrafast coherent radiation. The facility is based on the current state of the art technology, a Ti:sapphire based laser system.

4.3.3 Vis Near Field Microscopy

The Boston University Photonics Center has established an ultra-high resolution microscopy and spectroscopy facility utilizing near-field optical techniques. Present capabilities include super-resolution imaging of material and devices in the spectral range from the near-ultraviolet to the mid-infrared. Near-field scanning optical microscopy (NSOM) and spectroscopy is a recent technique where a tapered single-mode optical fiber probe is placed within a fraction of a wavelength of a sample and scanned over the surface. The tapered fiber provides a microscopic aperture through which the light is coupled. Because both the tip-to-sample separation and the tip aperture are a small fraction of the wavelength, the spatial resolution is given approximately by the tip diameter. Resolution as much as 20 times better than the best far-field microscope can be obtained.

High-resolution characterization of materials and devices is performed both by collecting emitted light in the near-field region and by local photo-excitation of the optically active material with light from the tip. Using wavelength tunable sources, near-field optical beam induced current measurements can provide information on the compositional and electronic structure of the semiconductor samples. NSOM can also be used to examine the evanescent fields of waveguides and couplers, the temperature profile in active devices, and various combinations of local excitation and collection of light. The examples below illustrate a few of these techniques.

4.3.4 Spectral Imaging of Laser Diodes

Collecting the light in the near-field from active optoelectronic devices has the capability to examine, with sub-wavelength resolution, optical mode profiles, carrier leakage, non-radioactive recombination centers, microscopic doping profiles, and local heat generation. Such detailed information is useful in examining reliability, failure modes, and operational characteristics of laser diodes. We have studied the optical mode structure and layer composition of high power laser diodes using the super-resolution capabilities of NSOM. At high current levels, coupling efficiency of the laser into a fiber amplifier decreases due to broadening of the spot size and the onset of multiple transverse modes, which limit the maximum useful power. Sub-micron collection mode imaging and spectroscopy mapping of the emission mode structure as a function of laser pulse length and current easily identify a regime of operation where multiple transverse modes are observed. Near-field microscopy enables the dynamic and spectral evolution of the character of the modes to be mapped out as a function of injection current and variations correlated with the layer structure of the device.

4.3.4.1 Near-field Optical Beam Induced Current

Using the probe as a highly localized light source allows the study of the microscopic photo-response of materials and devices. Termed NOBIC, for Near-field Optical Beam Induced Current, this technique has examined sub-micron imperfections in crystals, local carrier diffusion lengths in devices, and because the energy of photo-excitation is tunable, in the compositional mapping of layered and patterned semiconductors.

4.3.4.2 Near-field Thermal Imaging of Active Devices

With current trends toward sub-micron scale devices, power dissipation and elevated temperatures in high-density chips are becoming increasingly important issues. To study thermal phenomena on the microscopic scale, it is essential to develop a technique to measure temperature at sub-micron resolution. The spatial resolution of common optical temperature measurement techniques is determined by the diffraction limit at the radiation wavelength, which is ~5-10microns for infrared imaging. At this resolution, detailed and realistic thermal modeling and design optimization are impossible for even "large" micron-scale devices. Since near-field optical microscopy (NSOM) at infrared (IR) wavelengths is sensitive only to the emitted radiation, it operates in non-contact mode without effecting the operation condition of the device under test as well as allowing for operation in atmosphere. This project demonstrates an important use of NSOM to the semiconductor device manufacturing industry.

4.3.4.3 Spectral Mapping of Materials

Near-field microscopy has proven to be an important tool in correlating structural and compositional variations of materials with local optical properties. As an example, we have studied spectral near-field images of a color-center crystal planned for use in diode-pumped, intra-cavity doubling lasers by a major opto-electronics firm. Correlation between the structure in topography and the emission intensity has been mapped at a resolution beyond the diffraction limit. Other materials applications of NSOM include imaging of contact barrier height variations, analysis of defects and material composition, and mapping of luminescence efficiency.

4.3.5 Gamma Ray Imager For PET

A novel sensor system was developed for use as a component of a high-speed gamma ray tomograph. The detector system is designed for high collection efficiency and a very high rate capability, thus minimizing the time required for tomographic data acquisition. The device incorporates both a newly-developed high-speed and high-brightness inorganic scintillator (LSO), and a new optical means for the scintillator readout using wavelength-shifting optical fibers.

In the wavelength-shifting fiber readout, several crystals may be flexibly coupled to a single photosensor channel through optical multiplexing. Light emerging from a scintillator crystal enters through the side of a wavelength-shifting fiber, where it is absorbed and isotropically re-emitted. A fraction of the re-emitted light is trapped within the fiber and transported to a photosensor; the wavelength-shifting process allows one to inject light through the side of an optical fiber rather than through its end(s). By affixing perpendicular fiber ribbons at the two ends of an array of scintillator crystals, one can optically encode the spatial address of the gamma ray/crystal interaction. For example, a 16 x 16 array of 1mm x 3mm x 30mm crystals can be packed into a 16mm x 48mm x 30mm block; with one fiber ribbon 16mm wide running along the 48mm direction, and a second fiber ribbon 30mm away running along the 16mm direction. In this way, 32 photosensor channels can be used to encode a crystal-of-interaction for 256 crystals. By exploiting this multiplexing, one can use one-to-one coupling of interaction sites to multianode photomultiplier tubes (MAPMTs) via the fiber ribbons.

Using wavelength-shifting PMMA fibers coupled to thin plates of LSO and MAPMTs, we have demonstrated spatial resolution of 2.2mm FWHM for photocapture events. With this sensor resolution, annihilation acollinearity dominates system resolution for any tomographic detector ring used for Positron Emission Tomography (PET).

4.3.6 Quantum Optics Microscopy

For hundreds of years, the microscope and telescope have allowed us to peek into domains invisible to the naked eye. Developed by Galileo in the early 1600's, these remarkable instruments continue to serve us nobly today. In recent years, optical imaging has undergone enormous expansion as light sources, optical components, detection systems, and computational methods have advanced significantly. Moreover, a dazzling array of new techniques have come to the forefront which take advantage of different optical properties of a specimen, e.g., absorptivity, refractive index, scattering cross section, fluorescence.

However, all of the instruments that have been developed to date rely on sources whose photons arrive randomly in time and position. The light is noisy; this is true of both natural and artificial sources: skylight, sunlight, starlight, incandescent light, fluorescent light, and laser light.

In recent years, new kinds of light (quantum sources) have been developed in which the intrinsic noisiness is reduced in one way or another. This attendant reduction of noise can, if harnessed properly, improve the fidelity of optical imaging. One such source of light is generated by splitting the individual photons in a laser beam into pairs of twin photons. As unlikely as it seems, this process,called nonlinear parametric downconversion, takes place when a laser beam illuminates a properly oriented nonlinear-optical crystal. Because they share the energy and momentum of the original photon, the twin photons are said to be "entangled" with each other.

Within the Boston University Photonics Center, twin-photon-beam optical-imaging systems are being developed in the Quantum Optics Laboratory. Two schemes are currently being implemented: direct two-photon imaging and entangled two-photon microscopy. Both provide substantial advantages over systems that make use of ordinary (noisy) light.

4.3.6.1 Direct Two-Photon Imaging

In this technique, one of the downconverted photon beams is used to image a specimen while the other is detected directly and used to monitor the arrival of photons at the specimen. Since the photon occurrence times in the two matching directions are identical, the sequence of current pulses produced in a detector element located at a given direction in the direct beam provides full knowledge about the sequence produced at the matching direction in the imaging beam. However, noise at the imaging detector comprises random photons not accompanied by twins; hence, noise reduction is readily achieved by eliminating imaging events that do not correspond to matching events in the direct beam. Using these principles, novel optical instruments can be constructed with the ability to extract ultralow-light-level images from noisy optical backgrounds with higher signal-to-noise ratio than afforded by conventional measurement techniques. We are currently constructing a coded-aperture imaging systems using this effect.

4.3.6.2 Entangled Two-Photon Microscopy

This technique shares many features in common with conventional two-photon-fluorescence microscopy which (like confocal microscopy) is useful for imaging small volumes of a sample with high spatial resolution. The standard technique operates in the following manner: when two photons are absorbed, a fluorescent probe linked with the specimen emits light that is detected using conventional means. Unfortunately, this approach requires exceedingly high light levels to insure that pairs of photons have a significantly large probability of arriving simultaneously, and such high light levels often cause photodamage and photobleaching of the specimen.

The use of twin-photon beams, on the other hand, involves pairs of photons that arrive nearly simultaneously. Absorption can therefore occur at substantially lower light levels, thereby averting damage to the specimen. Furthermore, because each photon of the pair comes from a different optical beam, the entanglement volume is adjustable so that an additional measure of control is available for selecting the location and size of the sample region desired. An entangled two-photon microscope is under construction in our laboratory.

4.4 Manufacturing

4.4.1 Compact Disc Manufacturing

We have developed a new process for CD stamper manufacturing. It replaces several difficult and failure-prone process steps with a radically improved, simpler alternative. In conventional mastering, nickel sub-master stampers are generated by electroforming from a glass master. The new stamper production technique replaces the conventional glass master substrate with a tough ceramic, and replaces several difficult electrochemical and manual operations with a single precision ion machining step, eliminating the need for a nickel sub-master. Processes that precede and follow stamper fabrication remain largely unchanged. To date, all critical process steps have been demonstrated. By eliminating the processes that are responsible for most of the toxic waste by-products (e.g. heavy metals, acids, and solvents) generated during stamper manufacturing, the new process is significantly cleaner. Since ion machining requires only several minutes, the overall processing time for fabricating a stamper is dramatically reduced. As a final benefit, the new technology eliminates all manual processes that are required in conventional stamper manufacturing, so substantial increases in yield are expected. By industry standards, this process represents a revolutionary change in optical disc mastering technology. The process is suitable for production of CD-audio, CD-ROM, and high density DVD (video) formats.

4.4.2 Optical Testing of Integrated Circuits

An optical methodology was developed to test electrical patterns on a microchip. The method involves placement of "optical probe points" at various locations in the microcircuit via a fluorophore design construct which is compact in size and specific to the semiconductor layer which carries the voltage or current of interest. The purpose of the structure is to allow the creation of an electrical field sufficient to cause optical properties of the surround to change and make the fluorophores emit when the test point is excited. The test structure has a physical design which creates sufficient electric field in a pattern which can easily be detected using a CCD camera.

4.5 Subcontracts

4.5.1 PRISM, Inc.

Compact Disk (CD) technology has become the basis of a range of industries since its initial standardization in the late 1970s. CDs and CD-ROMS, with data capacities on the order of 1 GB, are about to be supplanted by Digital Versatile Disk (DVD) technology, which offers about eight times greater storage. These optical storage devices are manufactured using fundamental replication methods that originated with vinyl 33 1/3 rpm records. The original data stream drives a laser to create a photolithographic mold on a glass substrate. The shallow mold is used with wet chemical electroforming to make a metallic master stamper, which is then used to mold replicas. This process is slow, prone to failures, and produces a process waste stream of hazardous solvents and heavy metals.

Boston University's Magnetic and Optical Devices Laboratory and the Center for Photonics Research worked with a small business, Prism, Inc., to address these problems. Prism's goal is to change the basic mastering technology from wet chemistry to ion machining. This process involves creating the original recording on a suitable substrate through photolithography, using the lithography as a mask (not as a mold), and ion machining the master stamper from the substrate.

Ion machining is an established technology for material removal that is widely used in the electronics industry as a means for forming thin layers of materials in devices and integrated circuits. A photolithographic mask protects areas that are to remain intact, and the bombarding ions remove materials in the open areas of the mask. The machining is used to remove materials from the substrate until the surface has exactly the shape needed for the master stamper. There is no wet chemistry electroforming because the substrate serves directly as the stamper.

Prism required that the laser writing process be identical to the conventional mastering process, and that the eventual stamper be compatible with standard CD injection molding systems.

4.5.1.1 Photoresist for Precision Ion Machining

Selection of an appropriate photoresist was the first task of this research. We have explored negative photoresists such that exposed areas are left intact during development. The mask and machined areas then have the required negative profile for injection molding. While there is more experience with positive photoresists, they would require additional process steps to give a negative profile.

Photoresist spin-on and exposure have been a second challenge. Our substrates already have a spindle hole, so the rheology of coating the substrate is different from conventional wafers. Thickness must be uniform and repeatable across the substrate. Photoresist thicknesses must be greater than in microelectronics applications because more material is removed and the mask must survive for a longer time in the ion beam. Feature aspect ratios can be as high as 4:1 and sidewall angles are critical to mold release. Because the thickness exceeds the write laser wavelength, there can be swing curve problems and power test bands were needed to establish proper exposure for each new substrate.

Ion machining has presented a third set of problems. Beam energies must be controlled to maximize processing speed, while at the same timee, not overheating the photoresist. Excessive beam heating can cause flow or crinkling of the photoresist, which are then replicated by subsequent ion machining. A particular concern has been the non-linear angle-dependence of material removal rates. This effect tends to attack edges and round them. It also causes sidewalls to retreat faster than flat surfaces, which tends to narrow features horizontally. Careful control of photoresist thickness and beam parameters can mitigate these problems.

DVD technology will benefit from the development of ion machining of stampers. DVD have smaller, more closely packed features, and their substrate thickness is half that of CDs. Removal of the electroformed metallic master stamper is proving difficult in a production setting. Since ion machining avoids this step, our process offers immediate advantages. The major scale-down problem for ion machining will be control of the sidewall shrinkage for the high aspect ratio mask features. It is believed that better photoresist curing, e.g. with UV exposure, will produce a more uniform removal rate with angle of incidence and reduce shrinkage.

4.5.2 Boston Communications Networks: Optical Tag Development

A project was initiated to develop a preproduction optical tag prototype to demonstrate manufacturable technology based on optical free space communication, integrated with advanced network hardware and an efficient access protocol. The communication link was based on infrared incoherent light to take advantage of the ubiquitous low cost LED components, and low power consuming electronics. An Olivetti Active Badge served as the IR transceiver. The IR front end communicated with a Philips PCD3350 microcontroller for wireless data transfer and remote programming. Other COTS components included Nexcom NexFlash NX25F011A flash memory, a Casio LMG-161C5-TPR 16 x 1 chip on glass LCD, and a Philips PCF8593 real-time clock.

5.0 Business Approach

5.1 Overview

Boston University created the Photonics Center as a new paradigm to strengthen and accelerate the product development process by joining university, industry, and government in close working relationships. The ONR Grant provided partial support for building construction, equipment purchase, administrative costs, and specific development projects with Navy and DoD application as described in Section Four. Its operating mode, which leverages the facilities and expertise of the university to do rapid prototyping via university/industrial teams in formal business partnerships, is focused on the critical problem of quickly introducing the most promising photonics ideas to the marketplace and assuring industrial sources for defense needs. The Center's laboratory building with state-of-the-art fabrication, measurement, and test equipment, together with its large base of experts, is a valuable asset for reducing financial and technical risk to both investment and industrial partners. The Center also provides a host of incubator functions from space to business services and assistance, including business plans and market analysis. The

Center is currently organizing access to venture capital in order to provide development capital for qualified companies. Only four years in operation, the Center has already successfully incorporated new technology into products and has initiated a significant number of joint development projects with industry.

5.2 Photonics Center: Commercialization Approach

The Center has developed and successfully implemented a technology commercialization approach based on making its assets available to the photonics industry and rapidly prototyping new products via university/industrial teams focused on quickly bringing the most promising ideas to the marketplace. To date, the Center's experience has enabled it to consider firsthand, in the context of concrete commercialization opportunities, how best to maximize the objectives of commercialization in a manner that is fully consistent with DoD goals.

The approach to commercialization developed by the Center is based on the premise that the selection and pursuit of commercialization opportunities should be based on incentives derived from the normal functioning of a competitive market. Traditional commercialization vehicles such as passive licensing, remain important elements of any commercialization program. However, they should be coupled with more innovative approaches that engage the entity making the key commercialization decisions, in this case the Photonics Center. Specifically, rather than relying exclusively on passive licensing of technology, the Center has developed a proactive approach that embraces the entire spectrum of vehicles and techniques used in company to company collaborations.

The core concept of this proactive approach is for the Center and a partner company to jointly develop a product by building prototypes on-site as a team. Since most product ideas will come from companies, the business infrastructure will already be in place. When this is not the case, additional corporate partners are involved in order to assure that ideas will be transformed into working products that are marketed, distributed, and supported. The Center brings facilities, expertise and access to investment capital, while the partner company brings ideas, the detailed knowledge of the market and the business infrastructure. The Center and the company make a business arrangement based on success. Neither benefit until the new product is profitable.

By placing its assets at commercial risk in a collective enterprise, the Center has an enhanced incentive to select commercial opportunities with real economic promise, and provide the enterprises with the continuing technical and business support critical to the success of such a venture. Accordingly, a fundamental element of the Center's commercialization approach is the principle that commercialization efforts should be carried out through enterprises in which the Center has a continuing economic stake; for example, an equity interest obtained in exchange for contribution of business expenses or for use of University facilities and equipment.

To fulfill this business model the Photonics Center has fulltime staff involved in structuring commercialization activities with industrial partners. In addition the Center also provides to its commercial partners:

- *Business Incubation Infrastructure*: Access to capital equipment and business service assistance.

- *Access to the Photonics Enterprise Advisory Board*: The Board is comprised of volunteers who have successfully founded or managed businesses in the past and who run key businesses such as banking, venture capital, and executive recruiting firms.

- *Access to Private Capital*: The Center is affiliated with a venture capital fund, Photonics Venture Partners, LLC, dedicated to photonics product development. In addition, Boston University maintains its own venture capital fund, The Community Technology Foundation.

6.0 Summary

The Boston University Photonics Center has been established to conduct basic and applied research on photonics materials, devices, and systems related to defense needs, and to establish research laboratories and facilities to support collaboration among academia, industry, and DoD in a consortium of efforts in Photonics for the New England area. The formal establishment of the Photonics Center provides application focus for the previous research and adds the role of photonics technology commercialization through emphasis on prototype product development in formal partnerships with industry and DoD. The Photonics Center is a continual resource to serve as a bridge between basic research and defense and industrial applications.

The resources required for photonics technology and product R&D and for the eventual commercialization of those technologies and products have been incorporated into the Photonics Center. These resources include people, laboratory facilities and equipment, technology innovations, and links with business. Several laboratory facilities have been established for conducting the technical efforts in materials and devices, systems development, and instrumentation, and thus cover the various aspects of technology and product synthesis, design, fabrication, and characterization. Further, these laboratories have been established with particular attention to assuring that the needed capital equipment and expertise will be available to move photonics technology from concept demonstration to prototype product development.

Technology development projects have been executed that cover a broad range of photonics technology areas, including optoelectronics materials and devices, portable spectroscopy, advanced instrumentation, visible and infrared near-field optics and applications, quantum optics, LCD modeling and fabrication, medical diagnostics and treatment using photonics, organic dyes for photochromic and laser applications, and magneto-optic materials and devices, among others. Business services have been established within the Photonics Center, including incubator space for joint prototype product development with industry and start-up companies, as well as access to market survey, planning, management, and professional services that provide the needed economic and business infrastructure for fully exploiting new technology development. Together, the various entities bring the ability to develop new photonics technology and products needed by DoD and industry, and help to assure a strong domestic photonics industry that secures for DoD access to technology for its needs.