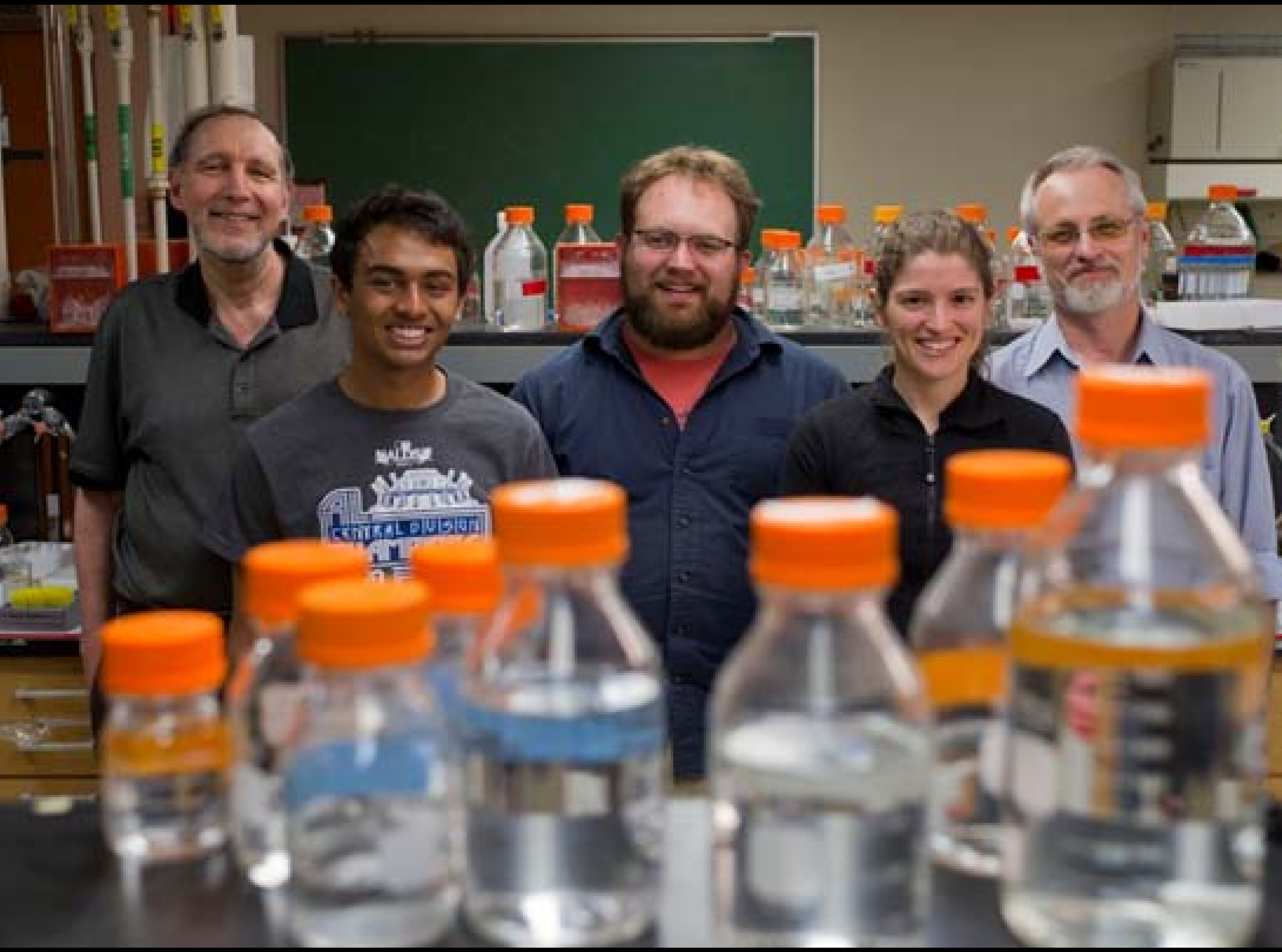


The Boston University
photonics
center

ANNUAL REPORT 2011-2012

LETTER FROM THE DIRECTOR

This annual report summarizes activities of the Boston University Photonics Center in the 2011-2012 academic year. In it, you will find quantitative and descriptive information regarding our photonics programs in education, interdisciplinary research, business innovation, and technology development

Located at the heart of Boston University's large urban Campus, the Photonics Center is an interdisciplinary hub for education, research, scholarship, innovation, and technology development associated with practical uses of light. Our iconic building houses world-class research facilities and shared laboratories dedicated to photonics research, and sustains the work of forty-two faculty members, nine staff members, and more than one hundred graduate students and postdoctoral fellows.

This has been a productive year for the Photonics Center, marked by the completion of the first year of the Industry/University Collaborative Research Center that has become the centerpiece of our translational biophotonics program that focuses on advancing the health care and medical device industries.

In the seven years I have served as Director of the Photonics Center, I have witnessed our transformation into one of the nation's leading academic institutions in photonics scholarship, while continuing an unparalleled record of success in photonic system prototyping for defense and industry.

In the following pages, you will see that the Center's faculty received prodigious honors and awards, attracted $15M in new research funds for the year, and generated scholarly publications at an unprecedented rate in all of the leading journals in our field. Faculty and staff also expanded their efforts in education and training, building on prior successes in the National Science Foundation sponsored sites for Research Experiences for Undergraduates and for Teachers. As a community, we hosted a compelling series of distinguished invited speakers, and emphasized the emergent research theme of neurophotonics at the Annual Future of Light Symposium.

On behalf of the Photonics Center's faculty, staff, and students, I thank you for your interest in our annual report.

Thomas Bifano
Director

CONTENTS

SUMMARY FY 2011-2012

This report summarizes activities of the Boston University Photonics Center during the period July 2011 through June 2012. These activities span the Center's complementary missions in education, research, technology development, and commercialization.

In 2010, the Photonics Center unveiled a five-year strategic plan as part of the University's comprehensive review of centers and institutes. The Photonics Center continues to show progress on the Photonics Center strategic plan and is growing the Center's position as an international leader in photonics research. For more information about the strategic plan, read the Photonics Center Strategic Plan section on page 11.

In research, Photonics Center faculty published more than 100 journal papers spanning the field of photonics. A number of awards for outstanding achievement in education and research were presented to Photonics Center faculty members, including a Presidential Early Career Award for Scientists and Engineers (PECASE) for Professor Altug, the Boston University Peter Paul Professorship for Professor Han, and a Dean's Catalyst Award for Professor Joshi. New external grant funding for the 2011-2012 fiscal year totaled $15.8M. For more information on our research activities, read the Research section on page 26.

In technology development, the close of FY11 marked the end of the Photonics Center's decade-long collaboration pipeline technology development with the Army Research Laboratory (ARL). The successful outcomes of that unique partnership include a compelling series of photonics technology prototypes aimed at force protection. Our direct collaboration with Army end users has enabled transformative advanced in sniper detection of bioterror agents, and nuclear threat detection. In the past year, the Photonics Center has expanded the scope of its unique photonic technology development program to include applications in the commercial healthcare sector. For more information on our technology development program and on specific projects, read the Technology Development section on page 52.

In education, 17 Photonics Center graduate students received Ph.D. diplomas. Photonics Center faculty taught 29 photonics courses. The Center supported a Research Experiences for Teachers (RET) site in Biophotonic Sensors and Systems for 10 middle school and high school teachers. The Photonics Center sponsored the Herbert J. Berman "Future of Light" Prize at the University's Science and Engineering Day. Professor Goldberg's Boston Urban Fellows Project started its seventh year. For more on our education programs, read the Education section on page 64.

In commercialization, the Business Innovation Center continues to operate at capacity. Its tenants include 11 technology companies with a majority having core business interests primarily in photonics and life sciences. It houses several companies founded by current and former BU faculty and students and provides students with an opportunity to assist, observe, and learn from start-up companies. For more information about Business Innovation Center activities, read the Business Innovation Center chapter in the Facilities and Equipment section on page 78.

Graduate Student Alket Mertiri listens to the speakers at the Future of Light Symposium.

Highlights for FY 2011-2012

External Grant Funding
External grant funding for the 2011-2012 fiscal year was over $15.8M. For the second year in a row, the Other category showed a marked increase. The Other category represents a variety of grants including the Department of Energy, Beth Israel Deaconess Medical Center, and Massachusetts General Hospital. The Other category accounted for 26% of funding, NIH accounted for 23% of funding, and DoD accounted for 21%.

Two New Photonics Center Faculty Members
This year, the Photonics Center welcomed Professors David Bishop (ECE, PHY), and Xin Chen (CHEM) to the community. The new faculty members' research is focused on low temperature physics and the surface chemistry of soft materials, respectively. Professor Bishop also leads the University's interdisciplinary Materials Division, which has become affiliated with our institute and is located in newly renovated Photonics Center space.

Five Companies Launched from the Business Innovation Center
The University's Business Innovation Center is host to 11 technology start-up companies. This past year, five incubator companies: ByteLight, CosMO Systems, Cyber Materials, MobiLIFE, and Zipcents, exited the incubation program as they expanded and grew their businesses or re-evaluated their business plans. Six new companies joined the Innovation Center: 1087 Systems, Applified, Clean Tech Open, J2P, TR Aeronautics, and Wanderu. The mix of companies includes: life sciences, biotechnology, medical devices, photonics, clean energy and engineering.

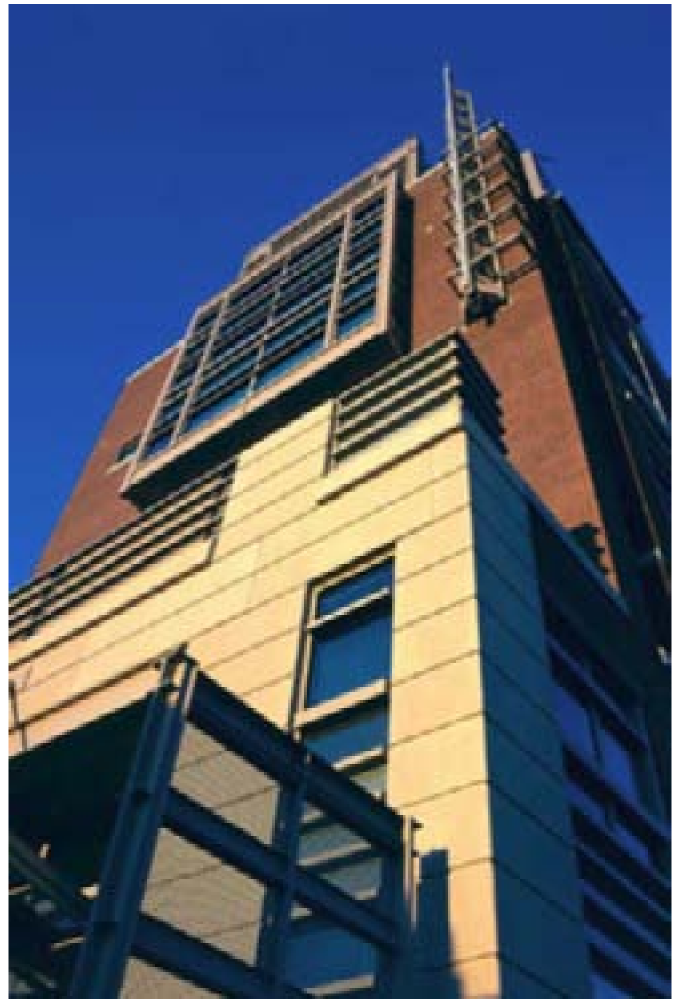
The 15th Annual Future of Light Symposium: Neurophotonics
This year, the symposium focused on optogenetics and neural imaging. Over 200 people from Boston University, other academic institutions and industry attended the event. A student poster session featured over 30 posters describing ongoing neurophotonics projects at the Photonics Center.

Institute Activities
In fulfillment of its broadened role as a university institute, the Photonics Center supported a number of initiatives to launch, promote, and sustain its affiliated Centers and Divisional units. Primary among these initiatives was the construction of a Materials Division shared laboratory, a research lab and office for the new director, David Bishop, and the allocation of provisional space for the division's planned new faculty laboratories. Additionally, institute programs included support for the Center for Nanoscience and Nanobiotechnology (CNN) nanomedicine initiatives, the Center for Space Physics student satellite program, and the NSF ERC on smart lighting.

Photonics Center at a Glance

Faculty Members	42
Staff Members	9
Funded R&D Projects	95
Funding for R&D (New funds for current year)	$15.8M
Photonics Courses	29
Archival Publications	136
Shared Laboratory Facilities	3

Mission and Highlights



The Boston University Photonics Center generates fundamental knowledge and develops innovative technology in the field of photonics. We work on challenging problems that are important to society, we translate enabling research discoveries into useful prototypes, and we educate future leaders in the field.

This mission is executed through:

- Basic research and scholarship in photonics
- Academic and entrepreneurial programs and initiatives for students
- Technology development for defense, security and healthcare applications
- Business innovation and commercialization of photonics technology

The Photonics Center community of faculty, students and staff engage in numerous interdisciplinary collaborations to further the field. Below are examples of how the Photonics Center and its diverse community execute on each of the four pillars supporting our mission.

Basic Research and Scholarship in Photonics

Photonics Center faculty are involved in research in diverse fields of study anchored by thematic areas of strength in biophotonics, nanophotonics, and photonic materials. Scholarship that has received prominent recognition and/or funding in the past year include:

- Research linking blast-related traumatic brain injury (TBI) and chronic traumatic encephalopathy (CTE) and validation of a model useful in developing new diagnostics, therapeutics and rehabilitative strategies for treating those injuries/diseases.
- Techniques for fault isolation in back-side analysis of next-generation semiconductor circuits using aplanatic solid immersion lens microscopy.
- Narrow-gap and wide-band gap materials, plasmonics and photonic materials for energy efficiency.

Academic and Entrepreneurial Programs and Initiatives for Students

While the Photonics Center does not offer academic degrees, its faculty teach a broad array of graduate and undergraduate courses that cut across traditional departmental curricula. Beyond the classroom, students engage in diverse entrepreneurial activities, ranging from engagement with companies in the Business Innovation Center to participation in the annual Future of Light Symposium.

Technology Development for Defense, Security, and Healthcare Applications
The Photonics Center's technology development activities focus on its long and successful record of prototyping for emerging photonic applications in defense and healthcare. The latter program grew substantially in the past year with the launch of an NSF-sponsored, member-supported Industry/University Collaborative Research Center on Biophotonic Sensors and Systems. That program and its corporate-sponsored applied research projects have become a prime focus for Photonics Center efforts in technology translation and prototype commercialization. The Cooperative Agreement with the US Army Research Laboratory had resulted in prototype insertions in DoD facilities, several start-ups, and established a model for technology translation that led to the launch and successful first year of operation for CBSS.

Business Innovation and Commercialization of Photonics Technology
The Photonics Center remains as a leader in commercialization of photonics technology, an activity anchored by its Business Innovation Center. Individual tenant companies continue to demonstrate growth and commercial potential and to attract business financing, while several new companies are launched annually with the support of the School of Management. Preferential selection of prospective tenants that work in areas allied with the research and scholarship activities of Photonic Center faculty members creates an environment rich with opportunities for collaboration and growth in sponsored research.

Participants view posters at the Research Experience for Undergrads (REU) and Research Experience for Teachers (RET) poster session.

PHOTONICS CENTER STRATEGIC PLAN

Central to the Photonics Center strategic plan is an operational model where the Center operates as a centralized institute – promoting, supporting, and sustaining allied research centers and programs across Boston University. This year, the Center has begun to execute on this vision and is effectively conducting business as an institute. The Charter and Bylaws approved by the Academic Advisory Board during FY11 outlines structure and purpose, membership policies, administration, organization, reporting, and budget and governance guidelines for the Center. A highlight of the Center's service as an institute this year has been its strategic partnership and support of the Materials Division. The Photonics Center managed a substantial renovation for the Materials Division in space formerly allocated to the Business Innovation Center. The Center will manage and maintain the Materials Division's new shared laboratory, and will oversee staff supporting that activity. The resources and expertise of the Photonics Center staff are employed to manage grants to several affiliated centers and labs, a key operational imperative of the strategic plan. These grants include: IARPA grant on back-side wafer analysis and training grants in conjunction with the affiliated Center for Nanoscience and Nanobiotechnology, faculty grants from NIH and NSF related to viral diagnostic technology, Research Experiences for Teachers, a substantial Research Experience for Undergraduates/Veterans program and a grant on Multi-scale multi-disciplinary modeling of electronic materials (MSME). MSME is a major four-year grant that will involve close collaborations with the ARL's research scientist at the Sensors and Electronic Devices Directorate (SEDD) and interactions with ARL's Enterprise for Multi-scale Research of Materials (EMRM), organizations that worked closed with the Photonics Center during the 10-

year collaborative research agreement with ARL.

In support of its strategic goal of expanding core programs for research support, the Photonics Center successfully launched and completed the first year of the I/UCRC on Biophotonic Sensors and Systems. Serving as the lead university of this I/UCRC, we have attracted the University of California at Davis as a partner site and eight corporate members. We expect to continue the growth of this I/UCRC with both additional university sites and additional corporate or government laboratories as members. With the support of the industry members, we have secured supplemental funding to the I/UCRC grant that has multiplied to the initial NSF funding more than tenfold.

A strategic area for growth and development at the Photonics Center has been is in the embryonic field of neurophotonics. Leveraging the mass media acclaim of Professor Goldstein's research linking blast-related Traumatic Brain Injury (TBI) and Chronic Traumatic Encephalopathy (CTE), strong young faculty involvement in optogenetic, neuro-engineering and neural-optical imaging research and I/UCRC members viewing treatment of neurological disease/injury as critical for future growth, the Center has already coordinated a number of efforts to establish a solid leadership position. To "kick-start" research initiatives and to build a network of corporate interest in the field, the BU Photonics Center chose Neurophotonics as the topic for the annual "Future of Light" Symposium held in December 2011. This symposium set records for overall attendance and corporate attendance with representatives from over 45 companies. Many of these companies are actively pursuing products addressing neurological disease and injury and could eventually be part of the I/UCRC. With the support of the I/UCRC members and key faculty, the Photonics Center subsequently won support for NSF Fundamental Research Program. The project concerns characterization of the molecular basis of optogenetic rhodopsin function, and it is expected to be the catalyst for expansion of our programs in neurophotonics.

A proposal to establish a five-year graduate education program (IGERT – Integrative Graduate Education and Research Traineeship) on Neurophotonics with strong support for innovation and entrepreneurial activities was submitted to NSF in an effort to link our emerging research strengths with a strong graduate training activity.

At the Business Innovation Center located on the 6th floor of the Photonics Center, Photonics Center staff have taken a leading role in setting the strategy and managing the operations. We are implementing strategic changes that align the business incubator more closely with ongoing Photonics Center member research and educational activities and with the activities of the new I/UCRC and its member companies.

Photonics Center staff continued to pursue high value, multi-investigator grants in the areas of terahertz devices, quantum communications, energy conservation and adaptive optics for space or ground surveillance. Staff contributions to support proposal preparation and networking with government, academic and industrial partners have become increasingly important to the Photonics Center's strategic mission, and that role will continue to expand in future years.

FACULTY AND STAFF

New Faculty Members

Professor David Bishop

Professor David Bishop is a Professor of Electrical and Computer Engineering, and Physics. He is the head of the Division of Materials Science and Engineering. In a career at Alcatel-Lucent spanning three decades, David advanced telecommunications, networking and cybersecurity solutions for the U.S. government market. An American Physical Society (APS) and Bell Labs fellow who holds 46 patents and has authored or co-authored about 250 publications, he earned his Ph.D. in Physics from Cornell University. His research interests include: low temperature physics, mechanical properties of materials at low temperatures, and MEMS and NEMS.

Professor Xin Chen

Professor Xin Chen is an Assistant Professor of Chemistry. The primary interests of his laboratory span many science and engineering fields including: physical chemistry, surface science, biophysics, materials science and biomedical engineering. He earned his Ph.D. from Stanford University. Following his Ph.D., he had two postdoctoral appointments. The first, from 2005 to 2008, was with Professor Paul Cremer, Texas A&M University, where he pioneered the use of vibrational sum-frequency spectroscopy to study interactions between macromolecular solutes and small molecule solvents and co-solutes. His second appointment, from 2008-2011, was with Professor George Whitesides, Harvard University, in the area of organic electrets (objects that bear a net charge) and elastic materials.

Faculty Member Listing

Hatice Altug
Associate Professor, ECE

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Research interests:
- Nanophotonic devices for optical communications
- Label-free biosensors

Richard Averitt
Associate Professor, Physics

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- Metamaterials & plasmonics
- Terahertz spectroscopy
- Correlated electron materials

Enrico Bellotti
Associate Professor, ECE

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- Semiconductor materials
- Parallel computing

Thomas Bifano
Professor, ME

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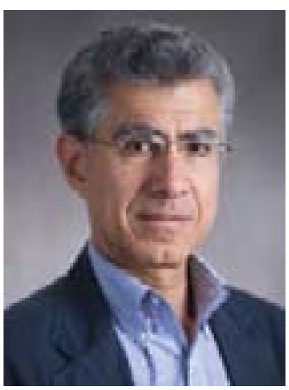
Research interests:
- Microelectromechanical systems
- Adaptive optics



Irving Bigio
Professor, BME, ECE

Office Address:
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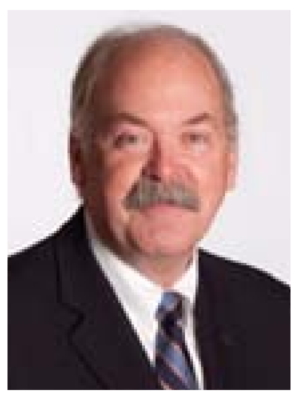
Research interests:
- Biomedical optics
- Medical applications of optics, lasers and spectroscopy



David Bishop
Professor, ECE, Physics

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Research interests:
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- Mechanical properties of materials at low temperatures
- MEMS and NEMS

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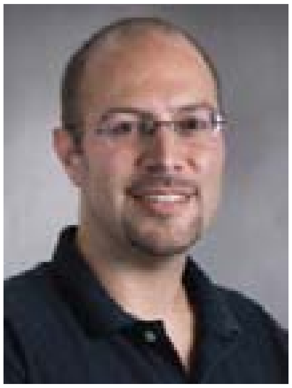
- Identification of biomarkers of infection
- Virus/host interactions



Luca Dal Negro
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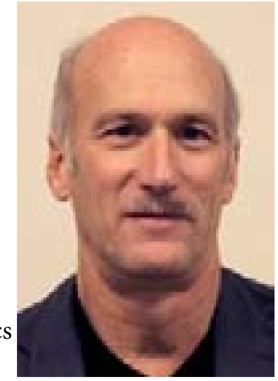
- Optics of complex media
- Computational electromagnetics



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Research Professor, BME

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Research interests:
- New instrumentation and methods for cell-based assays
- Deep-UV microscopy
- Microfluidics for assay of DNA

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- Nanofluidics
- Nanomechanics and NEMS

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- Quantum cascade laser sources
- Ultrafast infrared spectroscopy

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- Photonics applications

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- Rocket and satellite experiments

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- Femtosecond laser surgery

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- Semiconductor IC optical Failure Analysis
- Nanotubes and nano-optics

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- Alzheimers disease
- Biometals & metallomics
- Molecular aging disorders

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- Optical neural modulation
- Optogenetics

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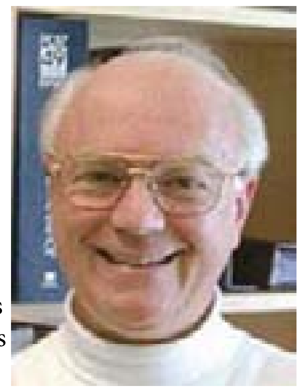
Research interests:

- Auditory physiology
- Neurocomputing and biosensors
- VLSI design of smart senor chips



Guilford Jones
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- Dye probes

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- Computer architecture

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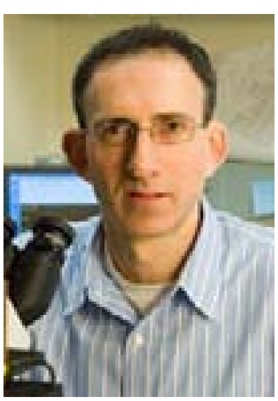
Research interests:

- Nanomechanics of hydrated biomaterials
- Microfluidic device design



Amit Meller
Associate Professor, BME

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- Ultrafast DNA sequencing
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Michael Mendillo
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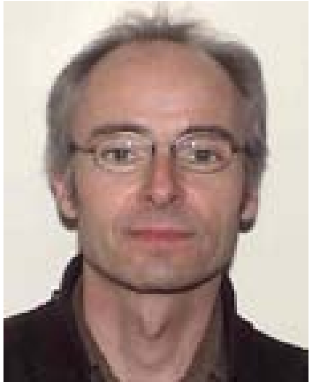
Research interests:

- Planetary atmospheres
- Space physics
- Observations and models



Jerome Mertz
Professor, BME

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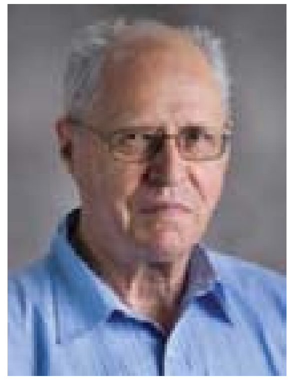
Research interests:

- Development and applications of novel optical microscopy for biological imaging



Theodore Morse
Professor Emeritus, ECE

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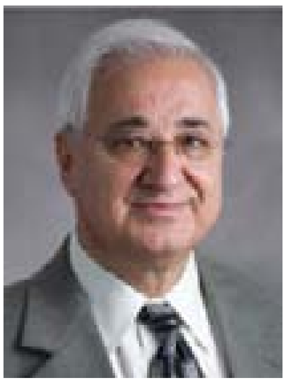
Research interests:

- Photonic material processing
- Optical fiber fabrication, lasers, and sensors



Theodore Moustakas
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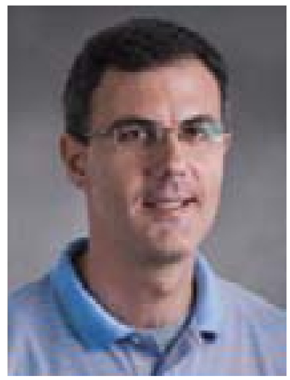
- Amorphous semiconductors



Roberto Paiella
Associate Professor, ECE

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- Design, implementation of new tools for manipulation of biological & inorganic materials

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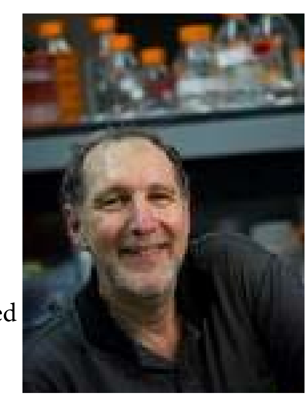
- Neurophotonic methods applied to the rodent whisker tactile system



Kenneth Rothschild
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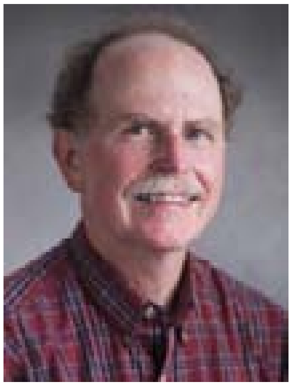
- Ion transport



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Research interests:
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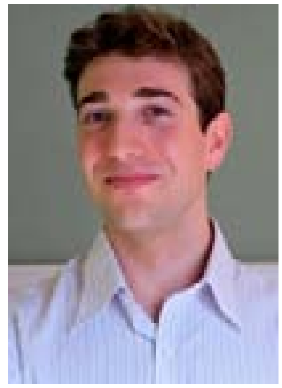
- Optical design
- K-12 outreach and education



Aaron Schmidt
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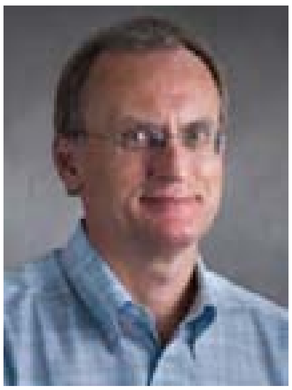
- Nanoscale energy transport
- Ultrafast laser metrology
- Laser-material interaction



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- Quantum biophotonics

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- Fiber optic manufacture
- Biomedical devices

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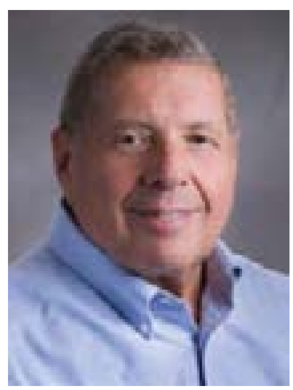
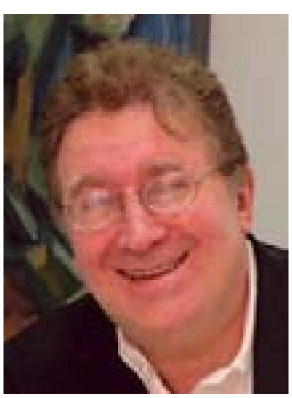
- Interactions of biomaterials with nanostructures
- Carbon nanotubes



Malvin Teich
Professor Emeritus, ECE, BME & Physics

Office Address:
8 Saint Mary's St.
Phone: 617-353-1236
e-mail: teich@bu.edu
Research interests:
- Quantum photonics
- Neural coding



Barry Unger
Associate Professor, MET

Office Address:
808 Commonwealth Ave., M15
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e-mail: unger@bu.edu
Research interests:
- Entrepreneurship and venture capital investment
- Innovation and product development process

Selim Unlu
Professor, ECE

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Research interests:
- Nanophotonics
- Biophotonics
- High-resolution optical microscopy

Xin Zhang
Professor, ME

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e-mail: xinz@bu.edu
Research interests:

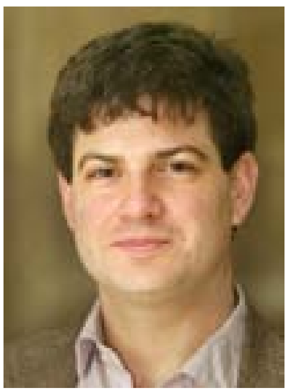
- Fundamental issues and applications of micro- and nanoelectromechanical systems (MEMS/NEMS or micro/nanosystems)

Lawrence Ziegler
Professor, Chemistry

Office Address:
8 Saint Mary's St., 719
Phone: 617-353-8663
e-mail: lziegler@bu.edu
Research interests:

- Spontaneous resonance raman studies of photodissociative and biological chromophores

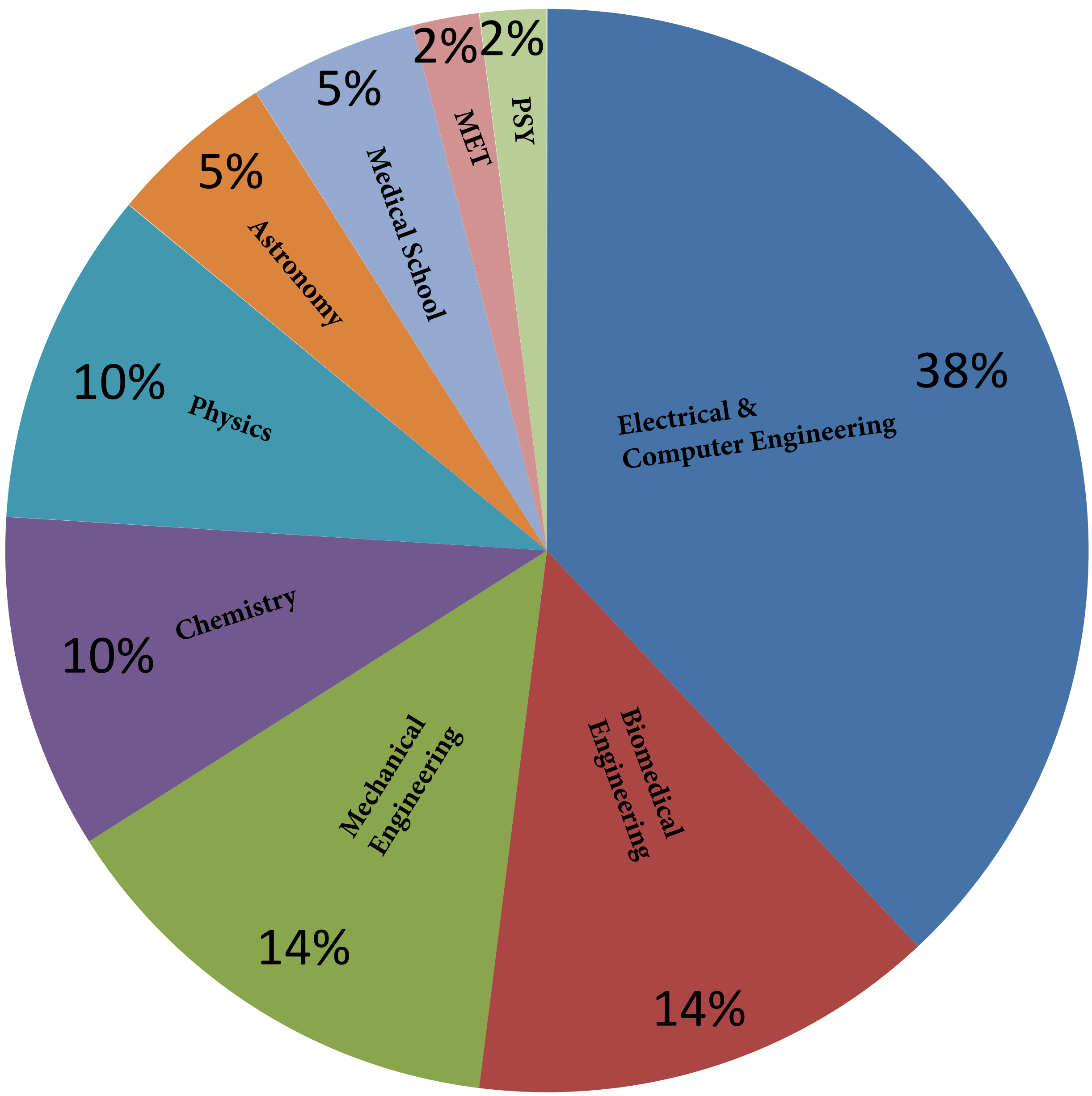
Visiting Professor



Jason Fleischer
Photonics Center Visiting Professor, 2011

Associate Professor, Princeton University

Primary Faculty Departments



Staff Member Listing

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Dr. Helen Fawcett
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Meghan Foley
Manager of Administration

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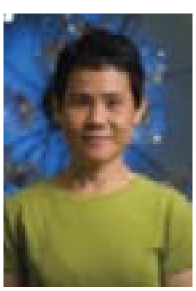
Tel: (617) 358-4438



Anlee Krupp
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Paul Mak
Laboratory Manager

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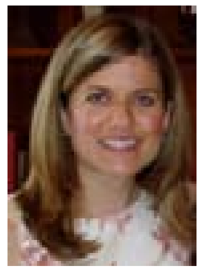

Beth Mathisen
Administration/Communication Coordinator

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Ryan Midura
Administrative Coordinator, Business Incubator

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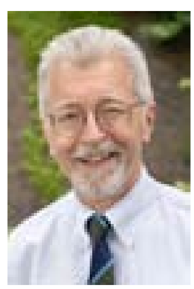
Tel: (617) 358-0480



Robert Schaejbe
Assistant Director, Operations & Administration

8 Saint Mary's St., 928
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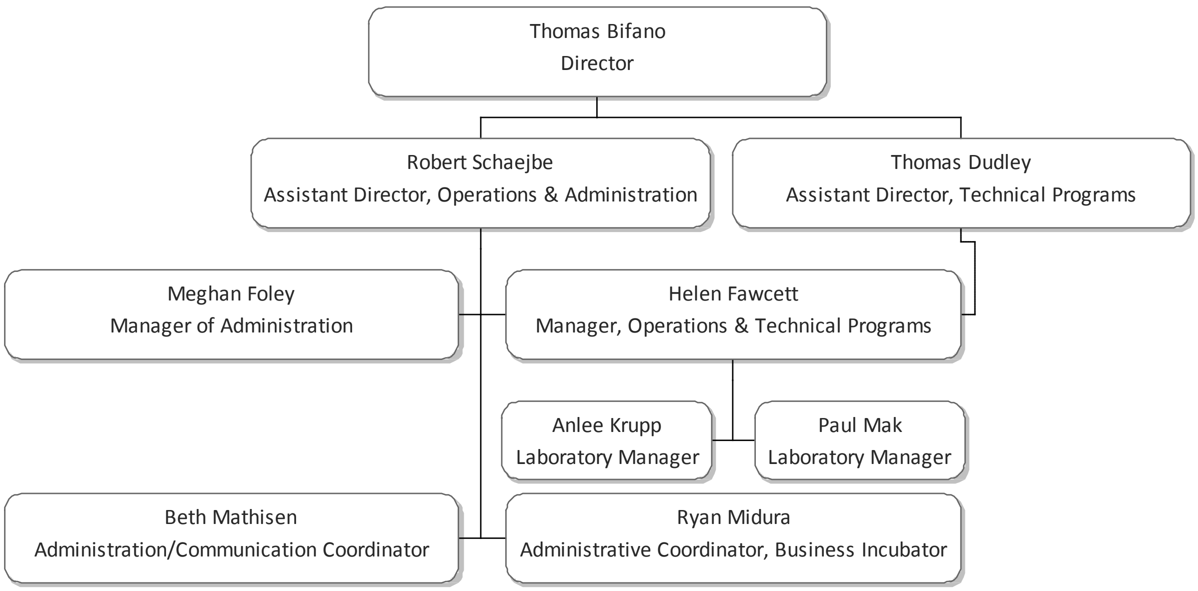
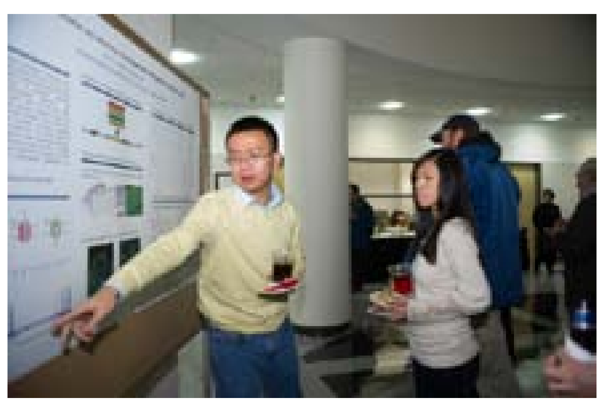
Photonics Center Organizational Chart



Research

The Photonics Center has a history of commitment to academic research. Its core shared laboratory facilities and multidisciplinary faculty laboratories provide fertile ground for seeding and cultivating discovery and innovation in photonics.

In the past year, Photonics faculty members received more than $15M in support from industry, academia and federal agencies including the National Science Foundation (NSF), the Department of Energy (DoE), the National Institute of Health (NIH) and the Department of Defense (DoD). One measurable outcome of our thriving research program was the collection of more than one hundred archival publications authored by Photonics Center faculty and students.



Externally Funded Research

Photonics faculty members received more than $15.8M in external funding. The following table lists funds in the fiscal year (July 1, 2011-June 30, 2012), as reported by the Office of Sponsored Programs.

P.I.	Dept.	Title of Project	Agency	Period	Amount
Altug	ECE	High-Performance Nanoplasmonic Sensors For Biological Warfare Detection	Department of Defense/Navy	5/1/10--4/20/13	$173,438
Altug	ECE	High-Performance Nanoplasmonic Sensors For Biological Warfare Detection	Department of Defense/Navy	5/1/10--4/20/13	$99,276
Averitt	PHY	SISGR: Multifunctional Materials Research Using Ultrafast Optical Spectroscopy	Department of Energy	9/1/09--9/14/12	$149,999
Bellotti	ECE	Photon-Trap Structures for Quantum Advanced Detectors (PT-SQUAD)	BAE Systems, Inc.	8/18/09--8/31/12	$47,000
Bifano	ME	Optical Propagation Through Impenetrable Materials Using MEMS	Keck Foundation	5/3/11--6/30/12	$17,500
Bifano	ME	I/UCRC Collaborative Research	I/UCRC: Industry Memberships	7/1/11--6/30/13	$200,000
Bifano	ME	I/UCRC Collaborative Research	I/UCRC: Industry Memberships	7/1/11--6/30/13	$50,000
Bifano	ME	I/UCRC Collaborative Research: I/UCRC: Center for Biophotonic Sensors and Systems (CBSS)	National Science Foundation	3/1/11--2/28/16	$80,000
Bifano	ME	I/UCRC Collaborative Research: I/UCRC: Center for Biophotonic Sensors and Systems (CBSS)	National Science Foundation	3/1/11--2/28/16	$8,000
Bifano	ME	Scalable, Cost-effective, High Actuator-Count Deformable Mirrors for Astronomical Adaptive Optics	National Science Foundation	7/1/11--6/30/14	$360,180
Bifano	ME	I/UCRC: Characterization and Bioengineering of Optogenetic Rhodopsins	National Science Foundation	7/1/12--6/30/13	$200,000
Bifano	ME	Photonics Research and Technology Insertion	Department of Defense/ARL	7/1/06--6/30/12	$66,562
Bigio	ECE	Enhanced Intraarterial Delivery of Chemotherapeutic Drugs to the Brain	NIH	9/1/08--7/31/12	$54,565
Bigio	ECE	Optical Imaging of Chemotherapy for Brain Tumors	NIH	4/1/11--3/31/13	$51,115

P.I.	Dept.	Title of Project	Agency	Period	Amount
Bigio	ECE	Training Program in Quantitative Biology and Physiology	NIH/National Institute of General Medical	7/1/12--6/30/13	$312,582
Connor	MED	Stage-Specific Inhibitors of Orthopoxviruses	NIH/National Institute of Mental Health	04/15/11--03/31/13	$40,913
Connor	MED	Microarray Processing and Analysis of Biological Samples from Non-Human Primate Models of Viral Infections and Human Clinical Samples Supporting USAMRID Grant: Identification of Biomarkers	NIH	12/30/10--12/29/12	$149,360
Connor	MED	Development and Characterization of Animal Models for Filoviruses	Department of Defense/Army	02/15/10--01/31/13	$325,319
Connor	MED	Development of Near Real-Time, Multiplexed Diagnostics for Viral Hemorrhagic	NIH/National Institute of Allergy & Infectious Diseases	08/01/11--07/31/16	$1,422,347
Dal Negro	ECE	Deterministic Aperiodic Structures for On-Chop Nanophotonics and Nanoplasmic Device Applications	Department of Defense/ AFOSR	10/1/09--9/30/12	$133,499
Fritz	AST	BUSAT2: The Boston Univeristy Student Satellite for Applications and Training	Department of Defense/ AFOSR	1/1/11--1/31/13	$39,809
Fritz	AST	The Loss Cone Imager (LCI) for the DSX Program	Department of Defense/Air Force	8/19/11--12/31/11	$13,911
Fritz	AST	The Loss Cone Imager (LCI) for the DSX Program	Department of Defense/Air Force	8/19/11--12/31/11	$220,000
Fritz	AST	The Cluster Rapid Investigation 2008-2011	NASA	7/1/08--7/16/12	$8,398
Fritz	AST	The Loss Cone Imager (LCI) for the DSX Program	DOD/AIR FORCE	4/1/10--4/1/13	$20,000
Goldberg	PHY	Graphene Membranes as Micro- and Nano-Pressure Sensors	Advanced Energy Consortium	3/1/09--12/31/12	$335,433
Goldberg	PHY	Summer Immersion Institutes	Stephen Bechtel Fund	12/31/06--10/1/12	$100,000
Goldberg	PHY	Boston University Cross-Disciplinary Training in Nanotechnology For Cancer	NIH/National Cancer Institute	9/01/10--7/31/15	$29,912

P.I.	Dept.	Title of Project	Agency	Period	Amount
Goldberg	PHY	Boston Univeristy Cross-Disciplinary Training in Nanotechnology for Cancer	NIH/National Cancer Institute	9/1/10--7/31/15	$286,961
Goldberg	PHY	Logic Analysis Tool	DCG Systems, Inc.	12/8/10--12/7/14	$262,890
Goldberg	PHY	Next Generation Solid Immersion Microscopy for Fault Isolation in Back-Side Analysis	Department of Defense/Air Force	11/10/11--11/9/14	$1,022,000
Goldberg	PHY	Boston Univeristy Cross-Disciplinary Training in Nanotechnology for Cancer	NIH/National Cancer Institute	9/1/10--7/31/12	$204,087
Goldberg	PHY	Boston Univeristy Cross-Disciplinary Training in Nanotechnology for Cancer	NIH/National Cancer Institute	9/01/10--7/31/12	$82,874
Goldstein	PSY	Non-Invasive Detection and Molecular Analysis of Early Low X-Ray Dose Effects to the Lens	Department of Energy	9/01/09--4/30/12	$341,830
Goldstein	PSY	Personnel Agreement for Research Services of Olga Minaeva	VA Boston Healthcare System	8/01/11--9/30/11	$8,404
Goldstein	PSY	Personnel Agreement for Research Services of Noel Casey	VA Boston Healthcare System	8/01/11--9/30/11	$13,716
Goldstein	PSY	Personnel Agreement for Research Services of Juliet Moncaster	VA Boston Healthcare System	8/01/11--9/30/11	$10,929
Goldstein	PSY	Personnel Agreement for Research Services of Mark Wojnarowicz	VA Boston Healthcare System	8/01/11--9/30/11	$6,991
Goldstein	PSY	Effects of Space Radiation on Hippocampal-Eependent Learning and Neuropathology in Wild-Type and Alzheimer's Disease Transgenic Mice	NASA	9/01/11--8/31/14	$450,000
Goldstein	PSY	Metallomic Mapping of the Aging Brain in Trg2576 Transgenic Mouse Model	Cure Alzheimer's Fund	12/29/11--12/28/12	$100,000
Goldstein	PSY	Orally Active Bioavailable Metal Attenuating Compounds for Alzheimer's Disease	Alzheimer's Drug Discovery Foundation	10/01/11--9/30/12	$75,000
Han	BME	Blood-Brain Barrier Modification Using Heterotopic Nasal Mucosal Grafting for Enhanced Symptomatic and Disease Modifying Drug Delivery in Parkinson's Disease	Mass Eye and Ear Infirmary	7/20/11--3/20/12	$40,000
Han	BME	Cross Region Neural Computation Subserving Attention	NIH/National Institute of Mental Health	7/1/10--4/30/12	$51,934

P.I.	Dept.	Title of Project	Agency	Period	Amount
Han	BME	Functional Disconnection in Alzheimer's Disease and its Potential Rescue by Optogenetics	American Federation for Aging Research	7/1/11--6/30/12	$51,854
Han	BME	Cross Region Neural Computation Subserving Attention	NIH/National Institute of Mental Health	7/1/10--4/30/13	$243,205
Joshi	ECE	Career: System-Level Run-time Management Techniques for Energy-efficent Silicon-Photonic Manycore Systems	National Science Foundation	4/1/12--3/31/17	$271,852
Joshi	ECE	Electro-Photonic Nerwork-on-Chip Architectures in 1000+ Core Systems (ENEAC)	Department of Defense/ Army/RDE-COM ACQUIS	7/1/12--6/30/14	$149,332
Klapperich	BME	A Rapid PCR-Based, Point of Care (POC) Test to Discriminate Between Sterile and Infective SIRS	Beth Israel Deaconess Medical Center	10/1/10--9/30/11	$48,871
Klapperich	BME	Bacterial Drug Susceptibiility Identification by Surface Enhanced Raman Microscopy	Fraunhofer USA	7/1/10--6/30/12	$72,961
Klapperich	BME	Integrated Molecular Diagnostic System for Point-of-Care	BioHelix Corporation	9/30/11--8/31/12	$104,748
Klapperich	BME	Portable Low Power Nucleic Acid Extraction Module	Program for Appropriate Technology in Health	9/1/09--8/31/11	$51,164
Meller	BME	Single-Molecule DNA Sequencing With Engineered Nanopores	The Scripps Institute	9/1/10--6/30/12	$101,969
Meller	BME	Clare Boothe Luce Fellowships	The Henry Luce Foundation, Inc.	9/1/10--5/31/12	$30,822
Meller	BME	Single Molecule Sequencing by Nanopore Induced Proton Emission (SM-SNIPE)	NIH/National Human Genome Research Institute	7/20/10--6/30/13	$1,015,178
Mendillo	AST	FY 2011 DURIP: A North-South American Network of Magnetically Conjugate All-Sky Imagers for Ionospheric Space Weather	Department of Defense/ AFOSR	8/15/11--9/29/13	$170,000
Mendillo	AST	FY 2011 DURIP: A North-South American Network of Magnetically Conjugate All-Sky Imagers for Ionospheric Space Weather	Department of Defense/ AFOSR	8/15/11--9/29/13	$330,000

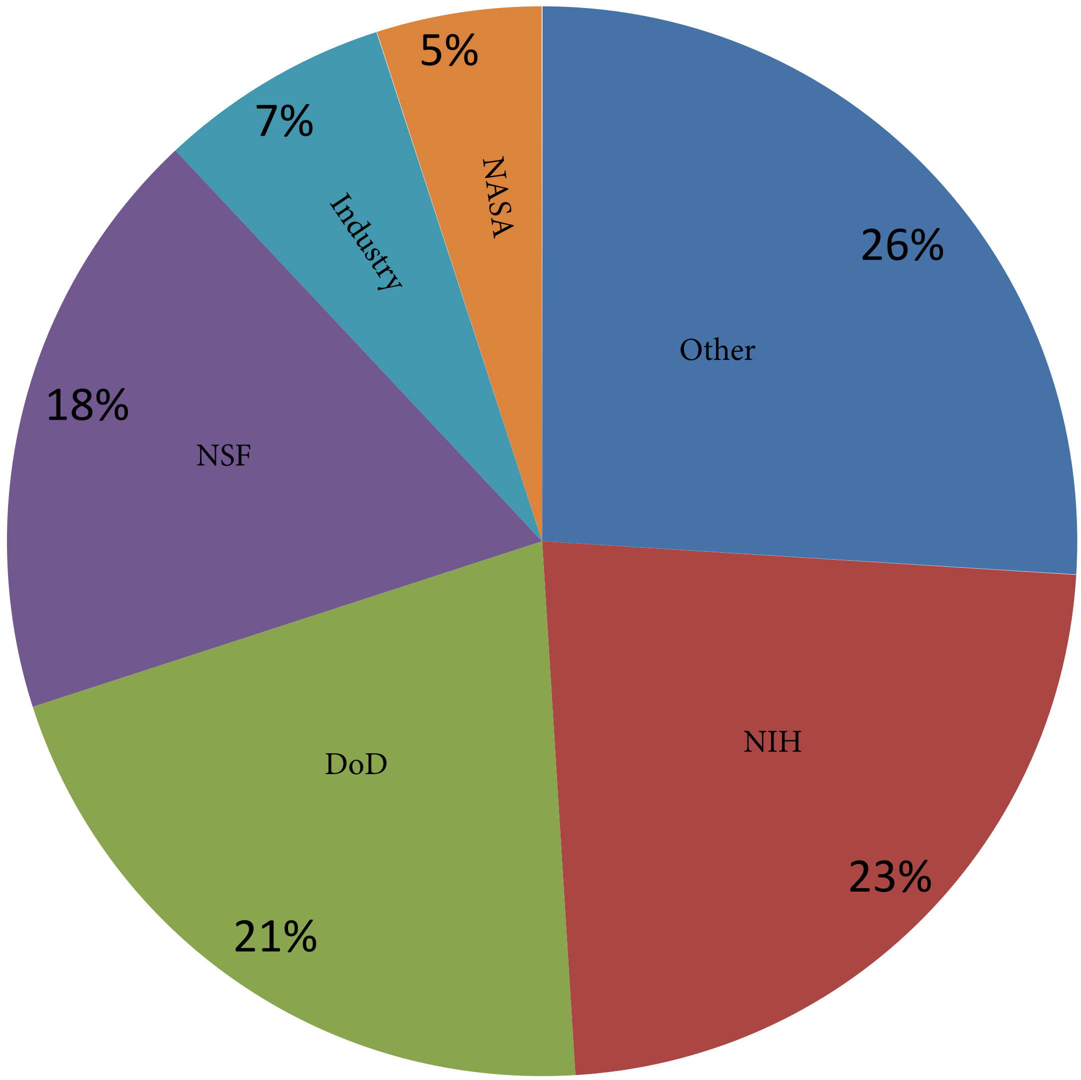
P.I.	Dept.	Title of Project	Agency	Period	Amount
Mendillo	AST	Imaging Science Investigations of Atmospheric Processes	National Science Foundation	12/1/11--2/28/17	$87,082
Mendillo	AST	Imaging Science Investigations of Atmospheric Processes	National Science Foundation	12/1/11--2/28/17	$260,137
Mendillo	AST	Inter-Hemispheric Studies of Ionospheric Irregularities	Department of Defense/ AFOSR	12/12/08--12/31/12	$95,000
Mendillo	AST	Mercury's Escaping Atmospher (Graduate Student: Carl Scmidt)	NASA	9/1/10--8/31/12	$30,000
Mendillo	AST	The Saturn Ionosphere: Diurnal Variations and Low-Altitude Structuring	NASA	6/21/11--6/20/13	$95,527
Mendillo	AST	Inter-Hemispheric Studies of Ionospheric Irregularities	DOD/Navy	12/12/08--12/31/12	$95,000
Mendillo	AST	The Saturn Ionosphere: Diunal Variations and Low-Altitude Structuring	NASA	6/21/11--6/20/13	$95,527
Mertz	BME	Development of Photothermal Microscopy for Biomedical Applications	NIH/National Institute of Biomedical Imaging & Bioengineering	4/1/11--3/31/13	$204,563
Mertz	BME	Ultrasound-Enabled Two-Photon Fret Microscopy	NIH/National Institute of Biomedical Imaging & Bioengineering	4/1/11--3/31/13	$81,826
Mertz	BME	Billing Agreement: Off-Campus Support for Hao Wang	Massachusetts General Hospital	5/1/12--8/31/12	$11,570
Mertz	BME	Billing Agreement Off-Campus Support for Whan Wook Chang	Massachusetts General Hospital	5/1/12--8/31/12	$11,570
Mertz	BME	Development of Photothermal Microscopy for Biomedical Applications	NIH/National Institute of Biomedical Imaging & Bioengineering	4/1/11--3/31/13	$204,563
Mertz	BME	The Development of Hybrid Widefield Imaging of Out-of-Focus Background Rejection	NIH/National Institute of Biomedical Imaging & Bioengineering	9/30/09--6/30/13	$350,709

P.I.	Dept.	Title of Project	Agency	Period	Amount
Mertz	BME	Ultrasound-Enabled Two-Photon Fret Microscopy	NIH/National Institute of Biomedical Imaging & Bio-engineering	4/1/11--3/31/13	$81,826
Moustakas	ECE	Joint R&D Work Proposal between OSRAM/Sylvania and Boston University: Processing and Testing of AlGaN Wafers Provided by OSRAM/Sylvania	Osram Sylvania, Inc.	4/1/12--3/31/13	$75,052
Paiella	ECE	Plasmonic Nanostructures Integrated With Semiconductor Light Emitting Materials for Enhanced Efficiency and Functionality	Department of Energy	8/15/06--12/31/12	$155,000
Ramachandran	ECE	High Power Blue Green Lasers for Communications	Department of Defense/ONR	11/1/10--4/30/13	$430,000
Ramachandran	ECE	High Power Blue-Green Fiber Lasers	Department of Defense/ONR	7/15/11--6/14/12	$297,000
Ramachandran	ECE	Power Scalable Blue-Green Bessel Beams	Department of Defense/ONR	1/1/11--12/31/12	$200,000
Reinhard	CHEM	Illuminating Dynamic Receptor Clustering in the Epidermal Growth Factor Receptor	NIH/National Cancer Institute	6/1/09--4/30/14	$327,072
Reinhard	CHEM	Rationally Designed Plasmonic Nanostructures for Rapid Bacteria Detection and Identification	National Science Foundation	6/1/09--5/31/13	$1,962
Rothschild	PHY	Melanopsin Signal Transduction Studied by FTSR Spectroscopy	NIH/National Eye Institute	9/1/10--5/31/13	$314,112
Ruane	ECE	RET-TRIPSS: Teachers' Research in Biophotonics - Sensors and Systems - Participant Support Costs	National Science Foundation	6/1/10--6/30/13	$10,000
Ruane	ECE	RET-TRIPSS: Teachers' Research in Biophotonics - Sensors and Systems	National Science Foundation	6/1/10--6/30/13	$10,000
Unlu	ECE	BU/CIMIT Applied Healthcare Engineering Fellowship	Massachusetts General Hospital	1/1/12--4/1/12	$83,698
Unlu	ECE	Graduate Assistance in Areas of National Need Fellowship in Nano-Bio Technology	Department of Education	8/16/10--8/15/13	$131,925
Unlu	ECE	High Throughput Quantification of Conformation and Kinetics of DNA- Protein Complexes	National Science Foundation	9/15/09--8/31/12	$110,000
Unlu	ECE	Multiplexed, Rapid, Point of Care Device to Quantify Specific Ige to Common Allergens	NIH/National Center for Health Research Resources	8/1/11--7/31/14	$204,375

P.I.	Dept.	Title of Project	Agency	Period	Amount
Unlu	ECE	Rapid Label-Free Single Virus Detection Platform for Multi-Pathogen Diagnostic	National Science Foundation	8/1/11--7/31/12	$149,999
Zhang	ME	Draper Laboratory Fellow: Aleksander Jonca	Charles Stark Draper Laboratory, Inc.	9/1/11--5/31/12	$29,820
Zhang	ME	Draper Laboratory Fellow: Else Frohlich	Charles Stark Draper Laboratory, Inc.	9/1/11--8/31/12	$39,761
Zhang	ME	Materials and Mechanics of Metamaterial Enhanced MEMS for Terahertz Technology	Department of Defense/ AFOSR	9/30/09--3/31/13	$130,000
Zhang	ME	Mercury Sensor Development for Application in the Oil and Gas Industry	Schlumberger-Doll Research Center	7/1/11--6/30/12	$56,752
Zhang	ME	Micro- and Nanoengineering Novel MRI Contrast Agents for Biomedical Sensing and Imaging	National Science Foundation	7/1/12--6/30/15	$335,719
Zhang	ME	An Impedence-Based Assay Microsystem for Real-Time High Throughput Study of Single Cells	National Science Foundation	10/1/09--9/30/12	$2,000
Zhang	ME	Materials and Mechanics of Metamaterial Enhanced MEMS for Terahertz Technology	DOD/AFOSR	9/30/09--3/31/13	$130,000
Zhang	ME	Micro- and Nanoengineering Novel MRI Contrast Agents for Biomedical Sensing and Imaging	National Science Foundation	7/1/12--6/30/15	$335,719
Ziegler	CHEM	Bacterial Drug Susceptibility Identification by Surface Enhanced Raman Spectroscopy	Fraunhofer USA	7/1/10--6/30/15	$34,032
Ziegler	CHEM	Bacterial Drug Susceptibility Identification by Surface Enhanced Raman Spectroscopy	Fraunhofer USA	7/1/10--6/30/15	$132,930

TOTAL: $15,839,027

Breakdown by Granting Agency FY 2011-2012



External Grant Funding for the 2011-2012 fiscal year was over $15.8M. For the second year in a row, the Other category showed a marked increase. The Other category represents a variety of grants including the Department of Energy, Beth Israel Deaconess Medical Center, and Massachusetts General Hospital. The Other category accounted for 26% of funding, NIH accounted for 23% of funding, and DoD accounted for 21%.

Calendar Year 2011 Publications and Patents

Book Chapters

H. Altug, R. Adato, S. Aksu and A. Artar, “Plasmonics and Plasmonic Metamaterials” by World Scientific in “Plasmonics for Ultrasensitive Nanospectroscopy and Biosensing.” Editor-in-chiefs are Profs. Shvets G., Tsukerman I, December 2011.

R.D. Averitt , “The Optical Properties of Metals: From Wideband to Narrowband Materials”, in Optical Techniques for Materials Characterization, edited by R. Prasankumar and A. J. Taylor, Taylor and Francis, 2011.

D.J. Kim, D.C. Mountain, and **A.E. Hubbard.** How Much Do Somatic and Hair Bundle Motility Contribute to Cochlear Amplification? What Fire is in Mine Ears: Progress in Auditory Biomechanics. American Institute of Physics (1403) Proceedings of the 11th International Mechanics of Hearing Workshop, Williamstown MA, pp 632-637, July 2011.

C.M. Klapperich and M. Mahalanabis, “Nanodevices for DNA Analysis,” in Encyclopedia of Analytical Chemistry, eds R.A. Meyers, John Wiley: Chichester. DOI: .1002/9780470027318.a9207, 2011.

R. Paiella, “Quantum Cascade Lasers,” in P. Bhattacharya, R. Fornari, and H. Kamimura, eds., Comprehensive Semiconductor Science & Technology, vol. 5, pp. 683-723, Elsevier, March 2011.

Journal Articles

H. Altug “On Chip Plasmonic Monopole Nano-Antennas And Circuits”. Nano Letters Vol. 11, pp 5219-5226, 2011.

H.Y. Tsai , P. Shi, M.F. Yanik, **H. Altug**, “Large- Scale Plasmonic Microarrays For Label-Free High-Throughput Screening”. Lab on a Chip Vol. 11, pp 3596-3602, 2011.

M. Dokmeci, **H. Altug**, “Flexible Plasmonics On Unconventional Substrates”. Advanced Materials Vol. 23, pp 4422-4430, 2011.

S.H. Mousavi, A. Khanikaev, J.H. Connor,, G. Shvets, **H. Altug,** “Seeing Protein Monolayers With Naked Eye Through Plasmonic Fano Resonances”, Proceedings of National Academy of Sciences (PNAS) Vol. 108, pp 11784-11789, 2011.

H. Altug, “Highly Directional Double Fano Resonances In Plasmonic Hetero-Oligomers”. Nano Letters Vol. 11, pp 3694-3700, 2011.

H. Altug, “Plasmon Induced Transparency In Cascaded P Shaped Metamaterials,” Optics Express, Vol. 19, pp. 22607-22618, 2011.

V. Liberman, T. H. Jeys, S. Erramilli, **H. Altug**, “Angle- And Polarization-Dependent Collective Excitation Of Plasmonic Nanoarrays For Surface Enhanced Infrared Spectroscopy,” Optics Express Vol. 19, pp. 11202-11212, 2011.

H. Altug, “Multi-Resonant Metamaterials Based on UT shaped Nano-aperture Antennas,” Optics Express

Vol. 19, pp. 7921-7928, 2011.

H. Altug, "Multi-Spectral Plasmon Induced Transparency In Coupled Meta-Atoms" Nano Letters Vol. 11, pp. 1685-1689, 2011.

C. Yilmaz, S. Somu, A. B. Busnaina, **H. Altug,** "Monopole Antenna Arrays For Optical Trapping, Spectroscopy And Sensing," Applied Physics Letters, Vol. 98, 111110, 2011.

D. Basov, **R. D. Averitt**, M. Dressel, D. Vandermarel, K.Haule, "Electrodynamics Of Correlated Electron Materials," Reviews of Modern Physics 83, 471-541, 2011.

Hu Tao, W. J. Padilla, **X. Zhang, R. D. Averitt**, "Recent Progress In Electromagnetic Metamaterial Devices For Terahertz Applications," (invited) IEEE J. Sel. Top. Quan. Opt. 17, 1077-260, 2011.

M. K. Liu, B. Pardo, J. Zhang, M. M. Qazilbash, S. J. Yun, Z. Fei, J.-H. Shin, H.-T. Kim, D. N. Basov, **R. D. Averitt**, "Photoinduced Phase Transitions By Time-Resolved Far-Infrared Spectroscopy in V2O3," Phys. Rev. Lett. 107, 066403, 2011.

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Patents

T Bifano (US Patent #7,929,195) MEMS Based Retroreflector.

Kenneth Rothschild (US Patent #7,897,335) Methods For The Detection, Analysis And Isolation Of Nascent Proteins.

Some Awards of Note

Hatice Altug received the Presidential Early Career Award for Scientists and Engineers (PECASE), the Popular Science Magazine Brilliant 10 Award, and the IEEE Photonics Society Young Investigator Award. She was also invited to the U.S. National Academy of Engineering, Frontiers of Engineering Symposium.

Luca Dal Negro's student Sylvanus Lee won the OSA Prize "Emil Wolf Outstanding Student Paper Competition 2011" for his work "Isotropic Structural Color of Nanostructured Metal Surfaces."

Bennett Goldberg won the Collaborator of the Year Award, presented during the Department of Medicine annual dinner.

Xue Han was awarded the Boston University Peter Paul Professorship, and the Alfred P. Sloan Research Fellowship.

Ajay Joshi received the NSF Career Award.

Theodore Moustakas received the 2011 Distinguished Scholar Award of the BU College of Engineering.

Theodore Moustakas' PhD Student Dr. Yitao Liao placed first in the BU Institute for Technology Entrepreneurship & Commercialization $50K New Venture Competition.

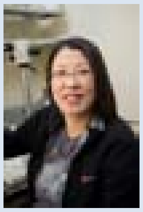
Barry Unger was the Taiwan Ministry of Education National Studies Scholar.

Xin Zhang was the Inaugural Distinguished Faculty Fellow (2009-2014) at Boston University.

Hatice Altug

Luca Dal Negro

Bennett Goldberg



Xue Han

Ajay Joshi

Theodore Moustakas

Barry Unger

Xin Zhang

Technology Development

The close of FY11 marked the end of the pipeline technology development program with the Army Research Laboratory (ARL) and the redirection of technology translation to the commercial healthcare sector. The 10-year long Cooperative Agreement may have ended, but technology development activities during FY12 reflect very positively on the experiences and relationships cultivated with ARL. The following developments reflect on work that benefited from prior activities with ARL.

Leading Activities for FY 2011-2012

- Research and development on an ARL funded project led by Professor Reinhard on Chemically Enhanced Photonic Crystals for Explosive Vapor Detection has continued with the project team actively pursuing collaborations in the private sector. One collaboration that has been gaining traction followed an introduction by Photonics Center staff that connected Professor Reinhard to Fraunhofer-HHI in Berlin. Here joint proposals have been made to federal agencies where international collaboration is welcome, post-doctoral researchers will operate out of the Reinhard lab on Fraunhofer funding and a visiting lecturer series is being set-up at the Photonics Center for FY13.

- The technology development and path to commercialization for a viral diagnostic tool has recently accelerated with the support of an NSF Accelerating Innovative Research (AIR) grant, a NIH grant and a partnership with BD (Becton, Dickinson, and Company). BD, a member of the I/UCRC on Biophotonic Sensors and Systems, is one of the largest diagnostic companies in the world. The viral diagnostic tool originally referred to as COBRA and developed with ARL funding and in collaboration with the US Army Medical Research Institute of Infectious Diseases now is the core technology behind the diagnostic tool commercialization efforts. The NIH awarded Professors Connor (PI) and Unlu (co-PI) a five-year grant for a project entitled "Development of Near Real-Time, Multiplexed Diagnostics for Viral Hemorrhagic Fever." In collaboration with BD and several other faculty, the PI/co-PI will deliver a production ready instrument integrated with microfluidics and sample preparation and ready for use in a BL-4 laboratory before the end of the grant. The NSF AIR grant provides funding for "Rapid Label-Free Single Virus Detection Platform for Multi-Pathogen Diagnostics." Year 1 of this two year grant was just completed with the delivery of an Alpha prototype that will be used by the Connor laboratory.

- Recent developments in membrane biophysics, neurophysiology and molecular biology have provided the catalyst for the birth of a new field termed optogenetics. In 2010, optogenetics was named the "Method of the Year" by *Nature* and listed first among the "Ten insights of the decade" by *Science*. Optogenetics relies on the expression of several unusual microbial rhodopsins in the neuronal membrane for light activating neurons or light silencing neurons. A core group of new and senior Photonics Center members are at the forefront of this fledgling field and during the final year of the ARL collaboration (FY11), a small amount of research seed funding was awarded to a project entitled: "Development of Light-activated Viruses and Rhodopsin Proteins for Selectively Engineering of Individual Nerve Cells in Complex Neuronal Circuits." In FY12 and with the support of the I/UCRC members, Professor Rothschild received an NSF award to further understand the molecular mechanisms of these proteins. The goal in this new grant will be to: characterize the molecular basis for function of key optogenetic rhodopsins and bioengineer improved versions for various neuroscience applications and use in living cells and neural circuits. A long-term goal here is potentially transformative approaches to study brain function, treatment for brain disorders and restoring vision for retinal degenerative diseases. This award was received at the end of the year and will run over the next fiscal year. This project will be driven by the I/UCRC with the key faculty contributors and is likely to be a start of larger programs in this field.

- Another ARL research seed project in FY11 that led to breakthroughs in FY12 was a project entitled "Development of High Resolution Laser Ablation Metallomic Imaging Mass and Optical Spectrometry (MIMOS) to Assess Microvascular Pathology in Traumatic Brain Injury (TBI) and Chronic Traumatic Encephalopathy (CTE)." This funding allowed Dr. Goldstein to complete the infrastructure required for his breakthrough research that linked TBI and CTE in blast-exposed military veterans. The models developed here will be useful for developing new diagnostics, therapeutics, and rehabilitative strategies for treating blast-related TBI and CTE. Dr. Goldstein has become a leading translational neuroscientist and his research has received acclaim in both scientific/medical journals and the mass media.

- During FY11, contacts developed by the Photonics Center staff at Battelle Memorial Institute led to sponsored research funding on Nanoplasmonic Rectenna Simulation and Development. The success of this project led to Battelle's support on an NSF AIR proposal that was submitted on a project entitled "Nanoplasmonic Metamaterial Antennae for Efficient Wireless Power Transmission." The proposal has several unique features to drive the translation of fundamental science and engineering discoveries into commercial reality and the success of the proposed project is dependent on the systems integration capabilities of Battelle and their support for entrepreneurial mentoring and commercialization. As we go to press with this annual report, we have learned that NSF has made the award to the BU Photonics Center.

- ARL has long supported materials development required to produce efficient deep UV LEDs. UV light at under 260 nm acts on micro-biological contaminants in water and air through a process by which adjacent thymine nuclei acids on DNA are dimerized, preventing replication of the micro-organisms, a process shown to be effective on E.coli, giardia and even more resistant virus strains such as adenovirus. In FY12, Rayvio, a startup company, spun out of BU with the assistance of the Office of Technology Development. Rayvio's core technology, a breakthrough crystal growth process for high efficiency deep UV LEDs was developed in Professor Moustakas' labs and licensed from BU. Rayvio plans to commercialize this technology for a $1+ billion market for water, air and food disinfection.

- BU was part of a team that proposed a comprehensive plan to address ARL's requirements in multi-scale, multi-disciplinary modeling of electronic materials (MSME). In the last quarter of FY12, BU's team known as "Computationally-Guided Design of Energy Efficient Electronic Materials" (CDE3M) was notified of this multi-year, multi-million dollar award. BU's efforts will focus on material simulations for III-Nitride based visible to UV light emitters, multi-spectral detector design, wide band gap power and RF devices, and devices for energy harvesting and power management. The research here needs to be responsive to the needs of the Army and focus on collaboration with the Army research scientist at the Sensors and Electronic Devices Directorate. The Photonic Center faculty (Professors Bellotti and Dal Negro) are major research contributors and leads on this project, and the team is also able to leverage the Photonics Center's extensive contacts and collaborative research track record with ARL to help make this project a success.

- Professor Klapperich, a leader in the field of microfluidics, was awarded an NIH training grant for a Center for Innovation in Point of Care Technologies for the Future of Cancer Care. This grant will start in FY13 and will focus on the identification, prototyping and early clinical assessment of innovative point of care technologies for treating, screening, diagnosis and monitoring of cancers. The Photonics Center will provide administrative management of this grant.

- Industry/University Cooperative Research Center (I/UCRC) on Biophotonic Sensors and Systems (CBSS) successfully completed the first year of operation with two university sites (BU and the University of California at Davis) and eight members (Agilent, Applied Precision – a GE company, BD Technologies, Fraunhofer-IPT, Lawrence Livermore National Labs, MIT-Lincoln Labs, Potomac Photonics, and Thorlabs). CBSS is one of about 50 I/UCRCs across the country and the only center focused on biophotonic sensors.

- On an organizational level the experiences of program management on ARL projects has resulted in a disciplined administrative and financial management skill set in the Photonics Center. In addition to the Photonics Centers' involvement in the above projects, the staff has also assumed financial and administrative management for:

o NSF Research Experiences for Teachers (RET) site in Biophotonics Sensors and Systems. Dr. Fawcett along with Professors Ruane and Brossman successfully completed year 2 of this three-year program that trains teams of teachers in very intensive "hands on" training in biophotonics and cleanroom activities.

o Department of Defense projects sponsored by the Intelligence Advanced Research Projects Agency(IARPA). Two grants from IARPA, a five year grant entitled "Next Generation Solid Immersion Microscopy for Fault Isolation in Backside Analysis" and another referred to as "Logic Analysis Tool," where BU is a subcontractor, draw financial and administrative management from the Photonics Center.

o Boston University's cross-disciplinary training program in nanotechnology for cancer (XTNC), formed by the Center for Nanoscience and Nanobiotechnology as an offshoot of BU's nanomedicine initiative, is training a community of scientists, engineers and medical researchers capable of working across disciplines, at the interface between nanotechnology and cancer medicine. Now in its third year, XTNC has supported twenty-six pre- and post-doctoral fellows with backgrounds in medicine, biology, and other health sciences, as well as in the physical sciences and engineering -- all engaged in interdisciplinary mentored research to develop novel nanoscale therapeutic and diagnostic tools for the detection and treatment of cancer.

Professor Enrico Bellotti and his graduate students conduct research.

The I/UCRC concept is a long-running NSF program designed to foster university and industry collaboration and is jointly supported by the foundation and industry. The mission of CBSS is:

- To create a national center of excellence for biosensor research with photonics as the enabling technology.
- To cultivate embryonic applications for biosensors.
- To advance biophotonic sensor technology, providing significant commercial benefits for disease diagnosis, patient monitoring, drug efficacy testing, and food and water safety.
- To develop effective methods for technology translation, accelerating innovative research to commercial benefit.
- To increase the quantity, quality and diversity of professionals prepared to work in this field.
- To involve the full technology and supply chain in a common focus of solving critical unmet needs in the healthcare sector using biophotonic sensing solutions.

Recommendations on research direction are provided by the Industrial Advisory Board (IAB) members (each member company has a representative on the IAB). The CBSS Center Director (Dr. Bifano) and the Site Director at UCD are responsible for reviewing the recommendations and making the final approvals. The projects approved for FY12 were as follows:

Project	Project Lead	University Site	Start Date	End Date
Label-Free Nanofluidic Nanoplasmonic Biosensor	H. Altug	BU	7/1/11	6/30/12
Photothermal Microscopy	S. Erramilli	BU	7/1/11	6/30/12
Live Cell Superresolution Microscopy	T. Huser	UCD	7/1/11	12/31/11
SERS for Rapid UTI Diagnosis	L. Ziegler	BU	1/1/12	6/30/12

The final reports for the three BU projects are presented below:

FINAL REPORT

Center for Biophotonic Sensors and Systems
Label-Free Nanofluidic-Nanoplasmonic Biosensor
(Covering research and results from July 1, 2011 through June 30, 2012)

Project Leader: Hatice Altug, Boston University, Electrical and Computer Department

Project Description: Demonstrate highly multiplexed, label-free, portable and rapid virus diagnostic technology that can be used by unskilled users to screen with minimal sample preparation large numbers of virus types that are relevant to global health.

Projected Milestones and Deliverables for July 1, 2011 through June 30, 2012

Milestones for the Current Proposed Year:	Deliverables for the Current Proposed Year:
• Demonstrate concentration limits, repeatability, and reliability for single virus type. • Demonstrate concentration limits, repeatability, and reliability for multiplexed viruses. • Evaluate sensitivity response to dust, biomass, and other environmental agents. • Establish a benchtop system for demonstration of detection technology.	• Identify limit of detection and sensitivity for individual virus family. • Validation of multiplexed reliability and repeatability – utilizing test platforms influenza and pseudotype VSV. • Fully functional system on the bench top that provides instant diagnostic.

Technical Results: The main objective of this one-year award was to demonstrate that a nanophotonic biosensor has the potential to be exploited for the development of a rapid, inexpensive, easy-to-use approach to detect and identify viruses from biosamples at clinically relevant concentrations. In the initial project, they proposed to look at application for PNA for virus detection. However, in August 2011 they had received an NIH grant that covered virus detection application of PNAs for hemorrhagic fever viruses. Accordingly, they changed the focus of PNA to detection of single and multiple protein detection in a protein microarray format.

The nanosensor used in this project is based on plasmonic nanohole arrays (PNA) that can optically sense the effective dielectric constant changes on the surface, therefore enabling detection of any binding process without the use of a label. With optimized surface chemistry, the sensor can be very specific for analyte capture. The detection is done in real time and allows kinetic rate measurement. Uniquely with respect to many optical biosensors, including other nanophotonic based approaches, plasmonic nanohole arrays operate with a collinear coupling scheme. Combined with the small footprint of sensors, this ability provides unique opportunities to realize multiplexing. The following technical results were achieved:
1) Demonstration of applicability of PNA structures for biosensing. This was completed by determining repeatability for bio-agent detection as well as evaluation of multiplexing capability and required large quantities of PNA chips. Within the initial stages of the proposal various fabrication strategies were evaluated. These include fabrication of PNA structures on:

- SiN membrane using electron beam lithography (EBL) at Boston University cleanroom as well as at Harvard University cleanroom (part of NINN).
- Glass substrate using electron beam lithography (EBL) at Georgia Institute of Technology cleanroom (part of NINN).
- Glass substrate using interference lithography (IL) at MIT in collaboration with Prof. Henry Smith.

According to SEM images, both interference and e-beam lithography methods for patterning nanohole arrays worked well once the fabrication procedure was optimized. Yield of successful PNA fabrication at BU and Harvard is low because of instability of dry-etcher. In particular, it has been concluded that fabrication facilities at BU were not suitable to result in repeatable wafer scale structures. It has been observed that substrate choice used for fabricating PNA structures introduces significant differences in spectral response thus the usability of the structures for biosensing. For protein and antibody detection both glass substrates and SiN membranes work. Although the glass substrate could be preferred due to better mechanical stability, it has been observed that it does not perform as well as SiN membranes. This is due to fact that glass substrate has lower refractive index than SiN (~1.45 versus ~2). We proposed that introducing a thin layer of silicon nitride (~150 nm) on glass can address the sensitivity limitation of glass. This layer, due to higher index, red-shifts the (1,0) mode located at the gold/substrate from the mode used for sensing. Although the structure is promising, due to lack of required nanofabrication equipment at BU cleanroom facility (and budget/time limitation to use Georgia Tech Cleanroom) we have not been able to test experimentally this proposed design.

2) In order to demonstrate repeatability and multiplexing capability for single and multiple kinds of proteins, a suitable surface chemistry procedure had to be developed. In particular surface had to be selective to detect proteins from complex solution. A surface functionalization procedure based on protein AG has been optimized.

3) Using PNA structures fabricated on a glass substrate with interference lithography and functionalized with protein A/G, we evaluated feasibility of multiplexed protein detection. IgGs obtained from different animals are used for bioagents. The chip contains arrays of sensor (and control) elements as shown in Figure 1a-1c. In our initial studies, we have been monitoring each sensor element on the chip serially, as we have been detecting the resonant shift using a spectrometer and a microscope system. But, this read-out scheme inherently reduces our multiplexing capability. In this study, we investigated use of an imaging method to monitor the resonance shift over the entire chip simultaneously. To detect resonant shift, we projected EOT signal through the entire chip onto a CCD and monitor the intensity variation with changing environment on each sensor unit at once as shown in Figure 1d.

On the sensor elements, we put antibodies that defined the word "hv." Addition of biomaterials result in resonance shift compared to the control elements as shown in Figure 2a. We have observed that for determining the intensity change on the chip after antibody immobilization using only a single light source centered at lambda 1 or 2 (obtained by filter) gives poor contrast between sensor and the control element as shown in Figure 2c-d. Instead, getting the EOT image at two colors and taking their ratio, we showed that we can improve significantly image quality for reliable bio-chem detection as shown in Figure 2b. In fact image contrast is much better than even fluorescence within the same data acquisition window.

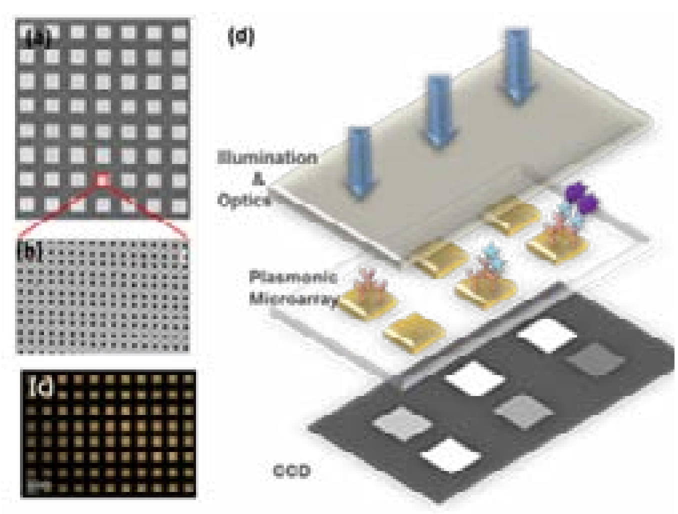


Figure 1 **(a)** SEM image of a fabricated PNA protein microarray on glass substrate by interference lithography (only 7x8 elements are visible in this image). Each sensor element is 20 by 20 um, and spacing between them is 15 um. **(b)** One element is zoomed. **(c)** CCD image of EOT from part of the chip (11x8 elements are visible). **(d)** Schematic of multiplexed protein detection with PNAs

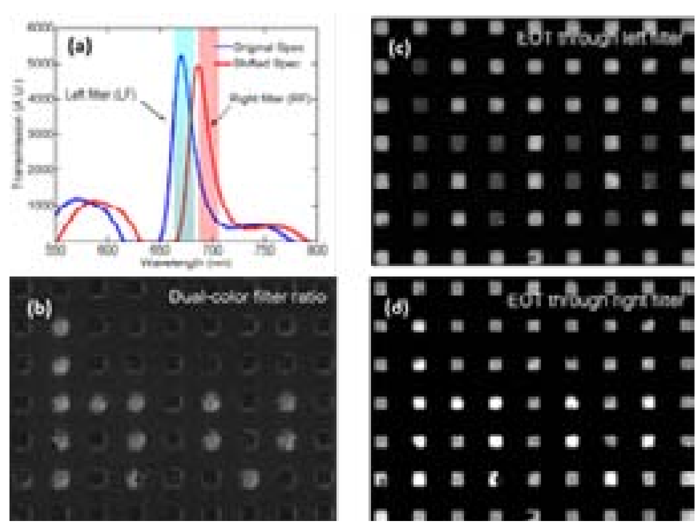


Figure 2 **(a)** Spectrum of EOT transmission from sensor element before and after antibody immobiliz ation illustrates red-shifting. **(b)**-**(d)** Antibody is im mobilized only certain elements in the array and defined word hv. On **(c)** and **(d)** resonance shift is determined as intensity shift when the EOT signal is projected on CCD with a left and right filter, respectively. On **(b)** their ratio is used. A better image contrast is visible in b compared to **(c)**-**(d)**.

Achievement of Objectives

[ ] Project targets 100% reached
[ ] about 75 % of the project targets are reached
[X] less than 50 % of the project targets are reached

Challenges or Problems:

- The original objectives could not be met because of another grant with similar objectives. For this program, when demonstrating protein detection, the project was able to demonstrate successful protein detection.

Explanation of Modifications to Original Proposal if Applicable:

- Instead of single and multiple kinds of virus detection, multiplexed protein detection has been investigated. This is due to acceptance of an NIH award on virus detection with PNA. Obtained results on protein detection are very promising.

Collaborative Activities:

- NA

Publications:

- M. Huang et al, "Large-scale Plasmonic Microarray: A New Approach for Label-Free High-Throughput Biosensing and Screening", Optical Society of America CLEO Conference, San Jose, CA, May 2012.

Patents or Intellectual Property:

- N.A.

Grant Submissions:

- R21 in preparation.

Current or Pending Funding Resulting From Research Results:

- N.A.

PI, Graduate Student, and Post-Doctoral Researcher Contact Information

- Dr. Maoqing Xin, Postdoctoral Researcher, Boston University Photonics Center

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FINAL REPORT
Center for Biophotonic Sensors and Systems
Photothermal Microscopy
(Covering Research and Results From July 1, 2011 Through June 30, 2012)

Project Leader: Shyamsunder Erramilli, Boston University, Physics & Biomedical Engineering

Project Description: The goal of this project is to develop photothermal microscopy and photothermal spectroscopy for label-free imaging and characterization of samples. The goal is to extend the rapidly evolving and exciting method for both wide-field imaging, and high-speed high-resolution microscopy.

Projected Milestones and Deliverables for July 1, 2011 through June 30, 2012

Milestones for the Current Proposed Year:	**Deliverables for the Current Proposed Year:**
• Build a prototype photothermal microscope and associated instrumentation for epi-detection with tunable laser sources and objectives in the vis-NIR-mid-infrared region. • Measure and demonstrate contrast at the < 10^{-5} level	• Epi-detection system for imaging. • Photothermal spectroscopy on single cells to elucidate the contrast mechanism. • Comparison of coherent vs. incoherent sources • Report on the progress made in extensions of the novel methods.

Technical Results

We have successfully built working prototype photothermal microscopes for both transmission and epi-illumination geometry. One paper has been published, along with two conference reports and additional papers are in preparation. Fig 1 shows a schematic of the working prototype instrument. The pump source is a tunable Quantum Cascade Laser that excites the sample at a selected frequency in the mid-infrared tuning range of the laser. The pump laser intensity is modulated at a frequency of 100 kHz. A collinear near-IR laser is focused using the same objective. The photothermal signal from the probe laser is detected using a lockin amplifier phase-locked to the pump frequency. For comparison, the transmitted mid-infrared signal is detected using an expensive cryogenically cooled InSb detector. When the QCL amplitude is modulated, photothermal response in the sample leads to a change in the scattering of the visible/NIR laser. This heterodyne detection method shows tremendous advantages. It allows for the first time the ability to detect infrared spectra using sophisticated but inexpensive visible detectors. The signal-to-noise is far superior to those achievable by conventional absorption spectroscopy. Results obtained in both the linear and non-linear regime have been published in a refereed journal article.

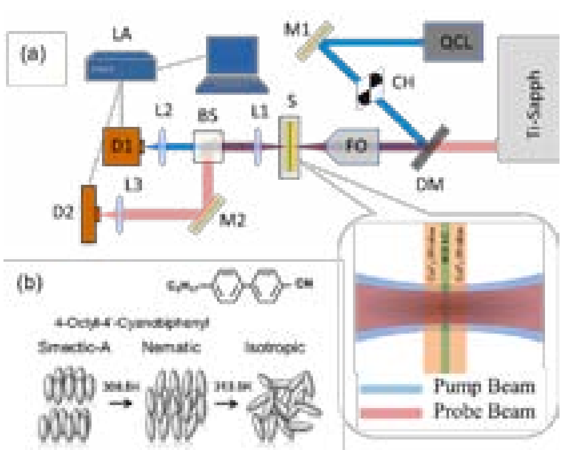


Fig 1. Schematic of the Photothermal Heterodyne Detection Scheme Used (A. Mertiri, BU Photonics).

Achievement of Objectives
[ ] Project targets 100% reached
[X] About 75 % of the project targets are reached
[ ] Less than 50 % of the project targets are reached

Remarks: The signal-to-noise of photothermal microscopy is excellent. To extend this to biomolecular studies, QCL tuned to protein absorption bands is all that is required.

Challenges or Problems:

- Designing an optical microscope that could work simultaneously in the visible, near-infrared and mid-infrared region is challenging. Conventional objectives are not achromatic over the entire range.
- The challenge was overcome by using all-reflecting objective, or using ZnSe objectives designed so that the pump region is larger than the probe region, eliminating or reducing edge effects.

Explanation of Modifications to Original Proposal if Applicable:

- Extension to protein absorption bands was not carried out because of the lack of availability for this project of a QCL that could function in the amide region. Instead, the QCL tuned to the 5- micron region was used as demonstration.

Collaborative Activities:

- A collaboration with MIT/Lincoln Labs has been very productive, with one paper published and another in preparation.

Publications:

- Mertiri et al, Applied Physics Letters, 101, 044102 (2012)

Patents or Intellectual Property:

- None

Grant submissions:

- In preparation

Current or Pending Funding resulting from research results:

- See above

PI, graduate student, and post-doctoral researcher contact information

- PI: Shyamsunder Erramilli, shyam@bu,edu
- Graduate Student: Alket Mertiri, amertiri@bu.edu

FINAL REPORT

Center for Biophotonic Sensors and Systems
A SERS Approach for Rapid Urinary Tract Infection (UTI) Diagnostics
(Covering Research and Results From January 1, 2012 Through June 30, 2012)

Project Leader: Lawrence Ziegler, Boston University, Department of Chemistry

Project Description: The goal of this project was to demonstrate that surface enhanced Raman spectroscopy (SERS) has the required bacterial concentration sensitivity and species/strain specificity to be used in clinical settings for the rapid (~30 min), reliable, easy-to-use, inexpensive diagnosis of bacterial pathogens in the urine of patients presenting with UTI symptoms. The successful development of this technology will lead to more accurate diagnosis of UTI and UTI-like presentations, and better determinations of most appropriate narrow-spectrum antibiotic within the timeframe of a patient's visit to a clinic/hospital and help reduce microbial antibiotic resistance in the long term.

Projected Milestones and Deliverables for January 1, 2012 through June 30, 2012

Milestones for the Current Proposed Year:	**Deliverables for the Current Proposed Year:**
• Demonstrate minimal bacterial sensitivity of 10^5 cfu/ml in spiked urine samples • Demonstrate species specificity for at least 5 species, >95% sensitivity and specificity • Demonstrate strain specificity for E.coli and K. pneumoniae • Show UTI diagnostic capabilities by blind testing bacteria spiked urine samples	A working and characterized platform for bacterial ID from urine for UTI diagnostics including: • Bacterial enrichment procedure from urine. • Demonstration of SERS sensitivity for UTI causing bacteria at medically relevant concentrations. • > 95 % sensitivity and specificity for species and strain diagnostic, blind testing of specificity.

Technical Results

The main objective of this very brief (6 months) award was to demonstrate that a surface enhanced Raman spectroscopy has the potential to be exploited for the development of a rapid, inexpensive, easy-to-use approach to detect and identify vegetative bacterial cells enriched from urine samples at clinically relevant concentrations. The following technical results were achieved supporting the goals of this project:

- <u>A simple preliminary bench top procedure was devised to enrich bacterial cells from spiked human urine samples for successful SERS data acquisition.</u> The sample preparation protocol for bacterial enrichment from spiked urine samples is summarized below:

1. Urine is collected into clean container from a healthy subject an hour or two prior to use and is kept at room temperature.
2. 50 mL of fresh urine is spiked with bacteria grown to log-phase. Bacterial growth medium is removed prior to spiking via centrifugation. Bacterial concentrations in urine from 10^4/mL to 10^8/mL were prepared as determined by calibrated OD measurements at 60 nm.
3. The sample is allowed sit for 1-2 hours at room temperature.
4. The sample is centrifuged for 10 min. at 5000 rpm at 18 C. Bacterial pellet is transferred to 2 mL vial and washed four times with Millipore water using repeated centrifugation.
5. Bacterial pellet is re-suspended in a final volume of ~ 10 mL . An enrichment factor ~103 was achieved. This factor was limited only by the ability to conveniently manipulate small volumes in bench top procedures.
6. ~1 mL of sample is placed on the SERS chip and air dried (5 min) for SERS spectral acquisition.

- SERS spectra of five bacterial species; E. coli, K. pneumoniae, S. saprophyticus, E. faecalis, Proteus were acquired from bacteria enriched spiked urine sample. Sample spectra are shown in Fig. 1. Data accumulation time ~10 sec, 785nm incident laser power ~ 1 mw. We could acquire SERS spectra from spiked urine samples that were as low as 10^4 cfu/mL. The minimum concentration for a UTI diagnosis is 10^5 cfu/mL. **Thus, SERS unequivocally has the ability to identify bacterial cells at clinically relevant concentrations.**

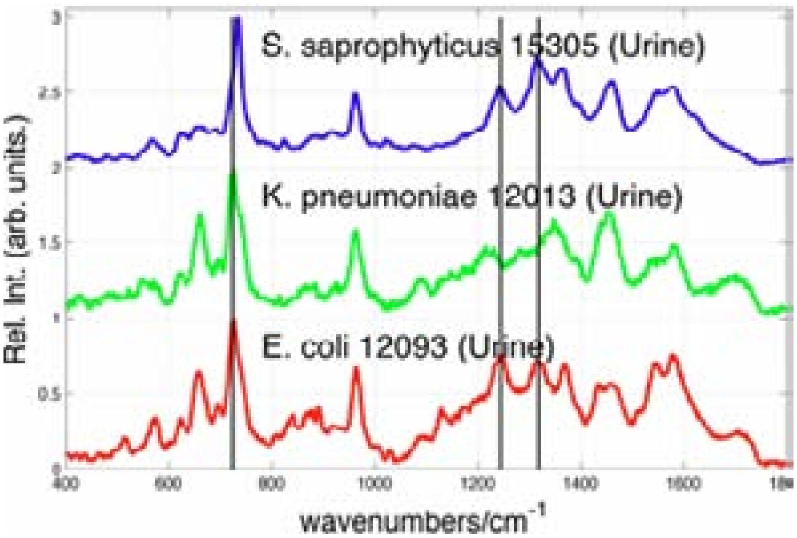


Fig. 1. SERS Spectra of Bacterial Cells From Spiked Urine Samples (105/mL) for Three Representative Species.

- The species specificity of these SERS signatures was demonstrated by the well-separated clusters derived from our unique barcode PCA analysis. An example is shown in Fig. 2 for a subset of these species. The excellent reproducibility for the SERS signatures of a given species is represented by the tightness of the clusters in Fig. 2. **In this limited initial data set, SERS signatures appear to have the specificity to allow their use as a diagnostic assay.**

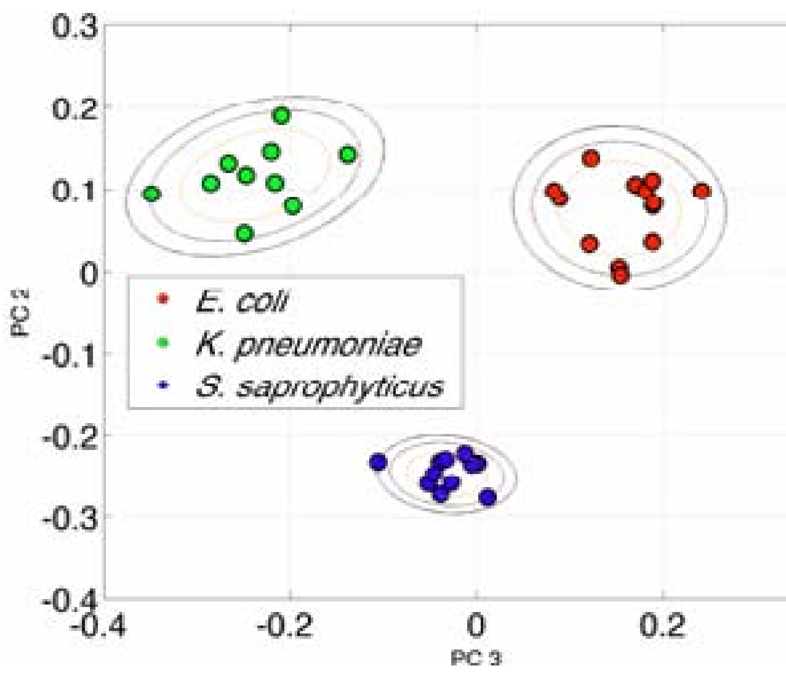


Fig. 2. PCA Clusters Generated by Our Unique Barcode Procedure Demonstrate Species Specificity.

- Strain specificity was also observed for 3 different strain of E. coli and K. pneumoniae enriched from urine spiked samples. An example is shown below in Fig. 3. Thus not only species but strain specificity has been demonstrated during this funding period. This is an important observation with respect to establishing drug susceptibility.

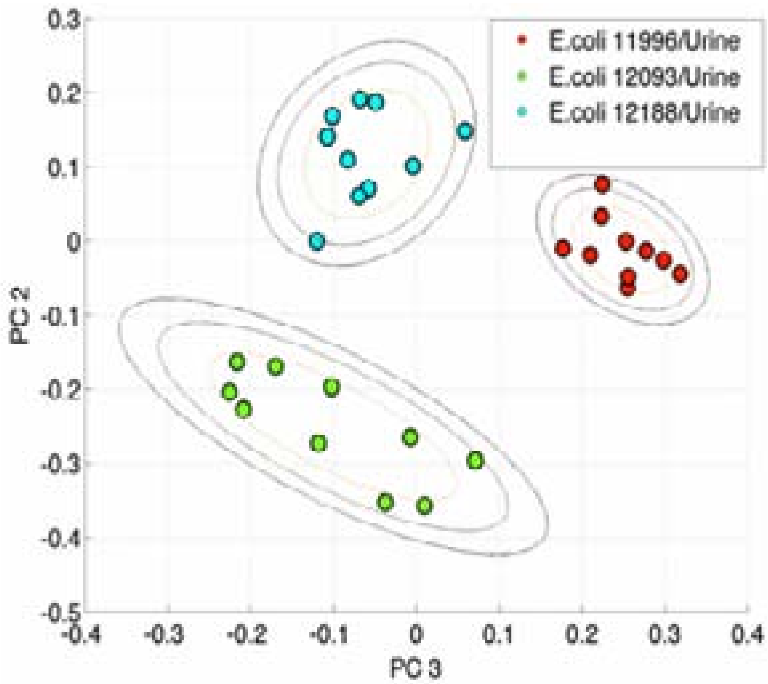


Fig. 3. Barcode PCA Clusters of SERS Spectra of 3 Strains of E. coli Enriched From Urine. This Technique has the Capability to Resolve Species.

- Blind testing of unknowns bacteria spiked into human urine was carried out for several strains of E. coli and K. pneumonia. All unknowns were identified at least within the confines of this preliminary data set library. An example of these results is shown in Fig. 4. The X corresponds to the blind tested unknowns correctly identified by this procedure following enrichment at 10^5 cfu/mL in urine.

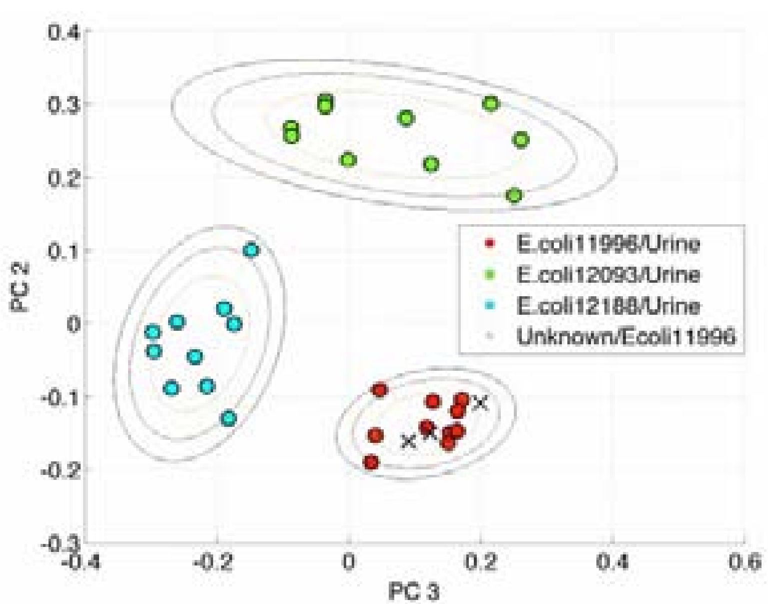


Fig. 4. This Barcode PCA Analysis Demonstrates the Successful Identification of a Blind Unknown E. coli Strain

(X) Enriched From Urine. The Unknown (X) Strain (EC 11196) Correctly Clusters with the Same SERS Spectra of This Strain in our Library.

Achievement of Objectives

[X] Project targets 100% reached
[ ] about 75 % of the project targets are reached
[ ] less than 50 % of the project targets are reached

Remarks: All project targets were achieved for the initial, relatively limited data of organisms. Follow-on work should expand this data set and corresponding reference library to a larger number of potential species and strains.

Challenges or Problems:
- Future challenges not explored in this initial short term proof of principle study include the effects of white blood cells and other body cells as found in real world clinical urine samples.
- The potential for quantification was not explored here.

Explanation of Modifications to Original Proposal if Applicable: NA

Collaborative Activities: None

Publications:
- "Rapid Bacterial Diagnostics Via Surface Enhanced Raman Microscopy", W. R. Premasiri, A. F. Sauer-Budge, J. C. Lee, C. M. Klapperich and L. D. Ziegler, Spectroscopy, 40-49, June 2012.
- "A SERS Diagnostic for Urinary Tract Infections", W. R. Premasiri, Y. Gebregziabher and L. D. Ziegler, (in preparation).

Patents or Intellectual Property: No new IP generated beyond existing patents.

Grant Submissions:
- NIH R21 in preparation.

Current or Pending Funding Resulting From Research Results:
- none

PI, Graduate Student, and Post-Doctoral Researcher Contact Information
- Dr. Ranjith Premasiri, Postdoctoral Researcher, ranjith@bu.edu, Boston University Photonics Center

The IAB met on two formal occasions during the year with several interim conference calls. The first formal meeting was actually the mid-year project status review with the IAB held at the Photonics Center on December 2, 2011. The annual program formulation meeting was held at UCD on April 30-May 1, 2012. Preceding the program formulation meeting was a formal process where a "Solicitation" for white papers was issued to faculty members of the Photonics Center and counterparts at UCD. The solicitation was generated with guidance from the IAB members based upon areas of research that best fit their respective company's product vision. In response to the solicitation, twenty-one white papers were submitted by faculty. There was a down-select by the IAB and nine of the white paper ideas were reviewed in much further detail during presentations to the IAB. IAB project ranking and recommendations to the Center Director ensued. The Center Director approved the projects as recommended by the IAB. The top three projects will be funded at the outset of the new fiscal year, with the start for the fourth delayed until new members (new sources of funds) are recruited.

Project	Project Lead	University Site
POC Cancer Detection From Serum	S. Unlu	BU
Snapshot 3D Flow Cytometry	J. Mertz	BU
Label-Free, Non-Genetic Method to Purify Stem Cell Derived Cardiomyocytes	J. Chan	UCD
Endoscopic Bessel Beam OCT	S. Ramachandran	BU
Monitoring Drug Dose Response of Single Cells Using Micro-Raman Spectroscopy	J. Chan	UCD
Direct Molecular Detection via SERS and Aptamers	S. Wachsmann-Hogiu	UCD

Education

One of the most important missions of the Boston University Photonics Center is education. Center faculty members teach photonics related courses, and also mentor undergraduate, graduate, and post-doctoral student and fellows working in their research laboratories.

Students participate in Photonics Center activities and work with the community in our shared laboratories. In the laboratories, students help train users and also assist lab managers with equipment troubleshooting and maintenance.

Each year, Center students participate in a variety of educational opportunities supported by Photonics Center staff. Students present during research poster sessions at the university-wide Science and Engineering Day and the Boston University Photonics Center Future of Light Symposium. These events give students the opportunity to highlight their cutting edge research and collaborations with the various departments. To further highlight the Center's commitment to a variety of student opportunities, the Center continued its support of the Research Experiences for Teachers (RET) and Research Experiences for Undergraduates (REU) in Photonics program.

Graduated Doctoral Students 2011-2012

PhD Graduate	Advisor	Primary Major
Nuno Almeida	Enrico Bellotti	Electrical Engineering
Suraj Bramhavar	Anna Swan	Electrical Engineering
Qingqing Cao	Catherine Klapperich	Mechanical Engineering
Kebin Fan	Thomas Bifano	Mechanical Engineering
John Henson	Luca Dal Negro	Electrical Engineering
Abhishek Jain	Lee Goldstein	Biomedical Engineering
Craig Keasler	Anna Swan	Electrical Engineering
Meghkun Liu	Richard Averitt	Physics
Benjamin McNally	Amit Meller	Biomedical Engineering
Alyssa Pasquale	Hatice Altug	Electrical Engineering
Jude Schneck	Lawrence Ziegler	Chemistry
Alon Singer	Amit Meller	Biomedical Engineering
Lynell Skewis	Bjoern Reinhard	Chemistry
Philipp Spuhler	Selim Unlu	Biomedical Engineering
Andrew Strikwerda	Richard Averitt	Physics
Brian Walsh	Theodore Fritz	Astronomy
Jane Zhang	Catherine Klapperich	Biomedical Engineering

Selected Photonics Related Courses

ENG EC 560 (Altug)/(Sergienko)
Introduction to Photonics
Introduction to ray optics; matrix optics; wave optics; Fourier optics; electromagnetic optics including absorption and dispersion. Polarization, reflection and refraction, anisotropic media, liquid crystals, and polarization devices. Guided-wave and fiber optics. Nanophotonics. Laboratory experiments: interference; diffraction and Fourier optics; polarization; fiber optics.

ENG EC 481 (Altug)/(Swan)
Fundamentals of Nanomaterials and Nanotechnology
Fundamentals of Nanomaterials and Nanotechnology encompasses the understanding and manipulation of matter with at least one characteristic dimension measured in nanometers with novel size-dependent physical properties as a result. This course explores the electronic and optical properties of material at the nanoscale and applications of nano-scale devices. The parallels between light and electron confinement are emphasized, e.g. in terms of normal modes, resonances and resonators, and the dispersion of light and electrons as affected by the periodicity of crystals and photonics crystals. Wave-mechanics and electromagnetics are reviewed and used to understand confinement and energy quantization. Nano-devices such as carbon nanotube transistors, nano-resonators, nanocavity lasers, nano-biosensor and their applications are discussed. Fabrication using top-down and bottom-up methods are discussed, as well as characterization using scanning probe methods, electron microscopy, and spectroscopic techniques.

ENG EC 574 (Bellotti)
Physics of Semiconductor Materials
This course teaches the relevant notions of quantum mechanics and solid state physics necessary to understand the operation and the design of modern semiconductor devices. Specifically, this course focuses on the engineering aspects of solid state physics that are important to study the electrical and optical properties of semiconductor materials and devices. Particular emphasis is placed on the analysis of the electronic structure of semiconductor bulk systems and low-dimensional structures, the study of the carrier transport properties and the calculation of the optical response that are relevant to the design and optimization of electronics and photonics semiconductor devices. The students will learn to apply the quantum mechanical formalism to the solution of basic engineering device problems (quantum wells, wires, and dots, 2D electron gas) and to perform numerical calculation on more complex systems (band structure calculation of bulk and low dimensional systems).

ENG EC 410 (Bellotti)
Introduction to Electronics
Principles of diode, BJT, and MOSFET circuits. Graphical and analytical means of analysis. Piecewise linear modeling; amplifiers; digital inverters and logic gates. Biasing and small-signal analysis, microelectronic design techniques. Time-domain and frequency domain analysis and design. Includes lab.

UHC EK 101 (Bifano)

Engineering Light

Engineers solve practical technical problems using an ever-evolving toolkit of modern technology. One of the most significant engineering advances of all time is optical imaging, the use of light-based technology to create representations of objects. In this course, students will learn how engineers make instruments that resolve structures as small as atoms, and as far away as the center of the galaxy. We will explore the common principles behind imaging instruments, and will probe new engineering advances that make it possible to see through "opaque" materials, to construct an invisibility cloak, and to seek earth-like extrasolar planets. Students will develop an understanding for challenges associated with microscopes that image deep within tissue for medical diagnosis and treatment, or night-vision goggles that allow seeing in the dark. The class includes lectures, interactive classroom activities, and hands-on laboratory exercises.

ENG EC 770 (Dal Negro)

Guided-wave Optoelectronics

Discussion of physics and engineering aspects of integrated optics and optoelectronic devices. Semiconductor waveguides, lasers, and photodetectors. Layered semiconductor structures, quantum wells, and superlattices. QW detectors, emitters, and modulators. OEICs. Photonic switching.

ENG EC 471 (Dal Negro)

Physics of Semiconductor Devices

Study of solid state electronic devices, including growth and structure of semiconductors, energy bands and charge carriers in semiconductors, junctions, diodes, bipolar junction transistors, field effect transistors and devices.

ENG BE 575 (Han)

Introduction to Neuroengineering

This course covers existing and future neurotechnologies for analyzing brain signals and for treating neurological and psychiatric diseases. It focuses on the biophysical, biochemical, anatomical principles governing the design of current neurotechnologies, with a goal of encouraging innovations of a new generation of therapies. Topics include basic microscopic and macroscopic architecture of the brain, the fundamental properties of individual neurons and ensemble neural networks, electrophysiology, DBS, TMS, various imaging methods, optical neural control technologies, optogenetics, neuropharmacology, gene therapy, and stem-cell therapy. Discussions of related literatures and design projects will be involved.

ENG EC 571 (Hubbard)

VLSI Principles and Applications

Very-large-scale integrated circuit design. Review of FET basics. Functional module design, including BiCMOS, combinational and sequential logic, programmable logic arrays, finite-state machines, ROM, and RAM. Fabrication techniques, layout strategies, scalable design rules, design-rule checking, and guidelines for testing and testability. Analysis of factors affecting speed of charge transfer, power requirements, control and minimization of parasitic effects, survey of VLSI applications. Extensive CAD laboratory accompanies course.

ENG EC 311 (Joshi)

Introduction to Logic Design

Introduction to hardware building blocks used in digital computers. Boolean algebra, combinatorial and sequential circuits: analysis and design. Adders, multipliers, decoders, encoders, multiplexors. Programmable logic devices: read-only memory, programmable arrays, FRGAs, Verilog. Counters and registers. Includes lab.

ENG EK 131 (Joshi)
Introduction to Engineering
Introduction to engineering analysis and/or design through a sequence of two modules or minicourses chosen from a selection of modules offered by participating engineering faculty. Each module presents students with key concepts and techniques relevant to an applied area of engineering. Limited to freshmen and sophomores (students with less than 64 credits toward degree requirements).

ENG BE 504 (Klapperich)
Polymers and Soft Materials
An introduction to soft matter for students with background in materials science, chemistry, and physics. This course covers general aspects of structures, properties, and applications of soft materials such as polymers, colloids, liquid crystals, amphiphiles, gels, and biomaterials. Emphasis on chemistry and forces related to molecular self-assembly. Topics include forces, energies, kinetics in material synthesis, growth and transformation; methods for preparing synthetic materials; formation, assembly, phase behavior, and molecular ordering of synthetic soft materials; structure, function, and phase transition of natural materials such as nucleic acids, proteins, polysaccharides, and lipids; techniques for characterizing the structure, phase, and dynamics of soft materials; application of soft materials in nanotechnology. Meets with ENG MS 504; students may not receive credit for both.

ENG BE 523 (Klapperich)
Mechanics of Biomaterials
Covers the chemical composition, physical structure, and mechanical behavior of engineering materials and the tissues they sometimes replace. Study of materials classes; materials selection; deformation of an elastic solid; yield and fracture; fundamentals of viscoelastic phenomena such as creep, stress relaxation, stress rupture, mechanical damping, impact; effects of chemical composition and structure on mechanical properties; methods of chemical property evaluation. Fracture and fatigue. Influences of plastics fabrication methods on mechanical properties. Emphasis on recent research techniques and results. Discussion of practical matters in medical device design including regulatory approvals, sterilization, packaging and quality control. Students will complete a semester-long design project. Same as ENG ME 523 and ENG MS 523; students can only receive credit for one of these courses.

ENG BE 773 (Mertz)
Advanced Optical Microscopy and Biological Imaging
This course will present a rigorous and detailed overview of the theory of optical microscopy starting from basic notions in light propagation and covering advanced concepts in imaging theory such as Fourier optics and partial coherence. Topics will include basic geometric optics, photometry, diffraction, optical transfer functions, phase contrast microscopy, 3D imaging theory, basic scattering and fluorescence theory, imaging in turbid media, confocal microscopy, optical coherence tomography (OCT), holographic microscopy, fluorescence correlation spectroscopy (FCS), fluorescence resonant energy transfer (FRET), and nonlinear-optics based techniques such as two-photon excited fluorescence (TPEF) and second-harmonic generation (SHG) microscopy. Biological applications such as calcium and membrane-potential imaging will be discussed. A background in optics is preferable. A background in signals and analysis is indispensable. In particular, the student should be comfortable with Fourier transforms, complex analysis, and transfer functions. Meets with ENGEC773. Students may not receive credit for both.

ENG EC 773 (Mertz)

Advanced Optical Microscopy and Biological Imaging

This course will present a rigorous and detailed overview of the theory of optical microscopy starting from basic notions in light propagation and covering advanced concepts in imaging theory such as Fourier optics and partial coherence. Topics will include basic geometric optics, photometry, diffraction, optical transfer functions, phase contrast microscopy, 3D imaging theory, basic scattering and fluorescence theory, imaging in turbid media, confocal microscopy, optical coherence tomography (OCT), holographic microscopy, fluorescence correlation spectroscopy (FCS), fluorescence resonant energy transfer (FRET), and nonlinear-optics based techniques such as two-photon excited fluorescence (TPEF) and second-harmonic generation (SHG) microscopy. Biological applications such as calcium and membrane-potential imaging will be discussed. A background in optics is preferable. A background in signals and analysis is indispensable. In particular, the student should be comfortable with Fourier transforms, complex analysis, and transfer functions. Students may not receive credit for both.

ENG BE 517 (Mertz)

Practical Optical Microscopy of Biological Materials

In this course students will learn the practice and the underlying theory of imaging with a focus on state-of-the-art live cell microscopy. Students will have the opportunity to use laser scanning confocal as well as widefield and near-field imaging to address experimental questions related to ion fluxes in cells, protein dynamics and association, and will use phase and interference techniques to enhance the detection of low contrast biological material. Exploration and discussion of detector technology, signals and signal processing, spectral separation methods and physical mechanisms used to determine protein associations and protein diffusion in cells are integrated throughout the course. Students will be assigned weekly lab reports, a mid-term and a final project consisting of a paper and an oral presentation on a current research topic involving optical microscopy.

ENG EC 591 (Paiella)

Photonics Lab I

Introduction to optical measurements. Laser safety issues. Laboratory experiments: introduction to lasers and optical alignment; interference; diffraction and Fourier optics; polarization components; fiber optics; optical communications; beam optics; longitudinal laser modes. Optical simulation software tools.

ENG EK 131 (Paiella)

Introduction to Engineering

Introduction to engineering analysis and/or design through a sequence of two modules or minicourses chosen from a selection of modules offered by participating engineering faculty. Each module presents students with key concepts and techniques relevant to an applied area of engineering. Limited to freshmen and sophomores (students with less than 64 credits toward degree requirements).

ENG EC 774 (Paiella)

Semiconductor Quantum Structures and Photonic Devices

Optical properties of semiconductors: interband optical transitions; excitons. Low-dimensional structures: quantum wells, superlattices, quantum wires, quantum dots, and their optical properties; intersubband transitions. Lasers: double-heterojunction, quantum-well, quantum-dot, and quantum-cascade lasers; high-speed laser dynamics. Electro-optical properties of bulk and low-dimensional semiconductors; electroabsorption modulators. Detectors: photoconductors and photodiodes; quantum-well infrared photodetectors. Same as ENG MS 774. Students may not receive credit for both.

ENG EC 577 (Ramachandran)

Electronic Optical and Magnetic Properties of Materials

This course in intended to develop an in depth knowledge of solid state concepts that are important for students in the areas of material science and electrical engineering. Specifically, this course focuses on the study of different apsect of solid state physics necessary to study technologically relevant crytalline and amorphous systems. Particular enphasis is placed on the study of the crystal structure, crystal diffraction and the related techniques used as diagnostic tools; the electronic, thermal, optical and magnetic properties of material systems important for electronics and photonics device applications. Furthermore the course will also consider the theory of superconductivity, the chemistry aspcts of solid state materials and will provide an introduction to solid state biophysics. This course complements EC 574 (Physics of semiconductor material) and EC575 (semiconductor devices) with its focus on technologically relevant structural, optical, thermal and magnetic material properties. Meets with ENG MS 577. Students may not receive credit for both.

ENG EC 568 (Ramachandran)

Optical Fibers and WaveGuides

Whether it be the FIOS™ internet connection at our homes, or fiber lasers powerful enough to cut metals (many automobile chassis are now made using fiber lasers), or the ability to perform endoscopic surgery and imaging, or doing frequency metrology with super-continuum sources (the basis of a few recent Nobel prizes)... the optical fiber has played a central, often dominant, role in many applications that impact the way we live. The main function of an optical fiber is to carry an electromagnetic (in the optical frequency) pulse over distances ranging from meters to greater than ten thousand kilometers without distortions. Fibers can also become smart light-pipes when they are intentionally designed to alter, temporally shape or amplify light pulses. Moreover, new developments in this field such as photonic bandgap fibers, fiber nanowires and higher-order mode fibers, are opening up new directions in science and technology. This course will introduce the optical fiber waveguide and its theory of operation. Specifically, the design and impact of the two most important properties in optical fibers -- dispersion and nonlinearity -- that govern the evolution of light in optical fibers, will be covered in detail. The latter part of the course will describe new fibers and fiber-structures that are active research topics today. One lecture of the course will include a tour of an actual, industrial-scale fiber fabrication facility.

ENG EK 307 (Ramachandran)

Electric Circuit Theory

Introduction to electric circuit analysis and design; voltage, current, and power, circuit laws and theorems; element I-V curves, linear and nonlinear circuit concepts; operational amplifier circuits; transient response of capacitor and inductor circuits, sinusoidal-steady-state response, frequency response, transfer functions; Includes design-oriented laboratory. (MET EK 317 and EK 318 fulfill this requirement; however, only 4 credits can be applied toward the graduation requirement.)

ENG EC 412 (Sergienko)

Analog Electronics

Continuation of SC 410. Topics include differential amplifiers, frequency response, operational amplifier structure and design, multistage circuit design, BJT, MOSFET, CMOS, and BiCMOS design principles, active filters and oscillators, and power devices. Includes lab.

ENG EC 762 (Sergienko)
Quantum Optics
Review of the postulates of quantum mechanics. Quantization of the electromagnetic field. Coherent, thermal, squeezed, and entangled states, and their associated photon statistics. Interaction of light with matter. Spontaneous and stimulated transitions. Theory of optical detection. Quantum theory of the laser. Interaction of light with two-level atoms, including photon echo and self-induced transparency. Quantum theory of parametric interactions.

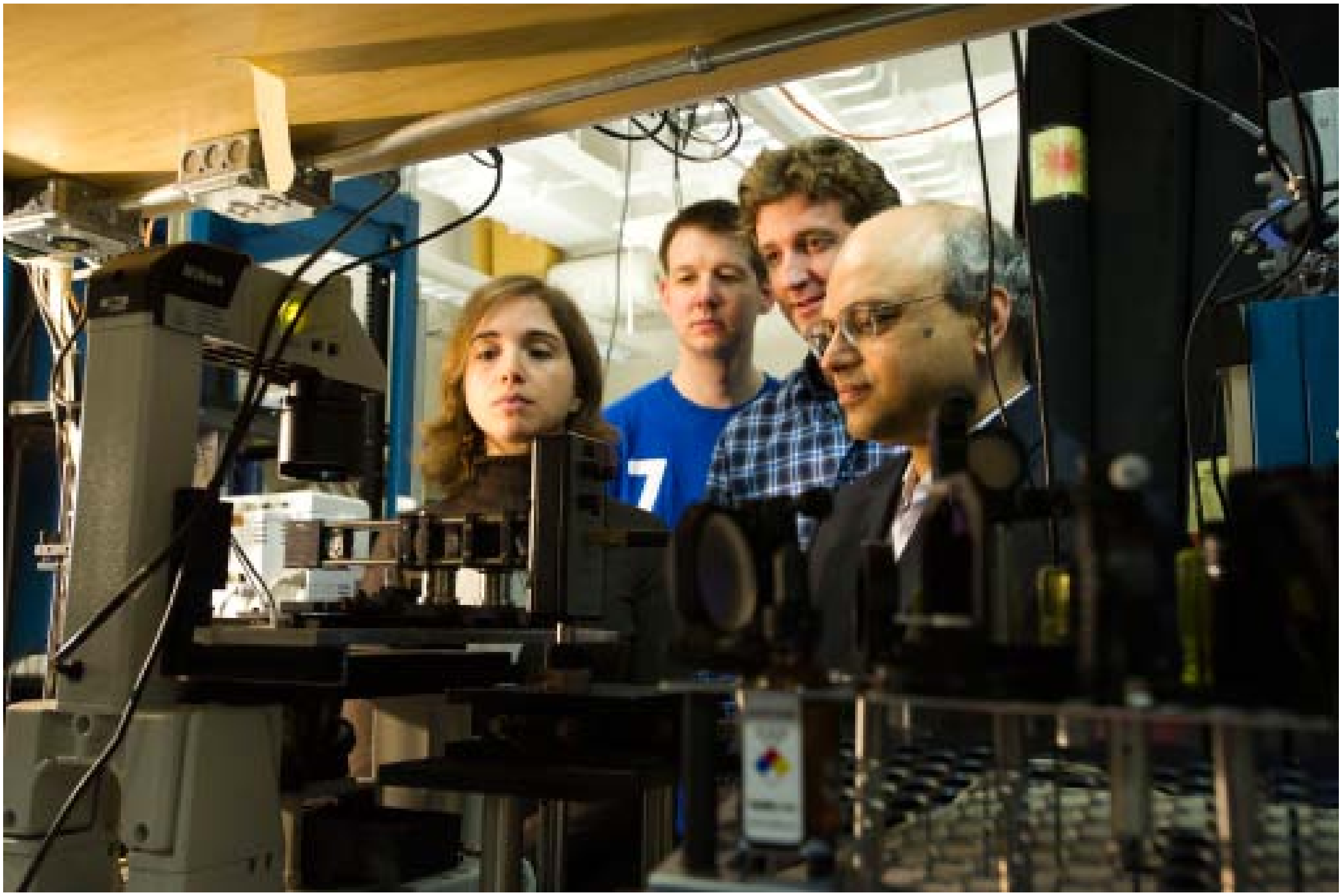
ENG EK 132 (Swan)
Introduction to Engineering
Introduction to engineering analysis and/or design through a sequence of two modules or minicourses chosen from a selection of modules offered by participating engineering faculty. Each module presents students with key concepts and techniques relevant to an applied area of engineering. Limited to freshmen and sophomores (students with less than 64 credits toward degree requirements).

ENG EC 764 (Swan)
Optical Measurement
The course begins with a review of classical electromagnetic radiation theory and properties of light such as polarization and coherence. In the first part of the course attention will be given to applications of interference and polarization effects used in different passive application areas such as resonators (e.g. sensors, switching and detection), visibility and interferometry measurements and the usage both of highly coherent and incoherent light respectively. The second part of the course will consider light-matter interactions in dispersive media and compare classical, semi-classical, and quantum mechanical models with focus on the two-level system. The analysis will be applied to active spectroscopy measurements such as absorption and transmission, Photoluminescence, Raman and IR in time and frequency domain measurements. The emphasis will be on extracting material morphology and material properties, illustrated with classical and current journal papers. Finally, we will also discuss relevant tools such as spectrometers and detectors.

ENG EC 570 (Unlu)
Lasers
Review of wave optics. Gaussian, Hermite-Gaussian, Laguerre-Gaussian, and Bessel optical beams. Planar- and spherical-mirror resonators; microresonators. Photons and photon streams. Energy levels; absorption, spontaneous emission, and simulated emission. Thermal and scattered light. Laser amplification and gain saturation. Laser oscillation. Common lasers and introduction to pulsed lasers. Photon interactions in semiconductors. LEDs, laser diodes, quantum-confined lasers, and microcavity lasers. Introductoin to photon detectors. Laboratory experiments: beam optics; longitudinal laser modes; laser-diode output characteristics.

ENG MS 778 (Zhang)
Micromachined Tranducers
The field of micro-electromechanical devices and systems (MEMS) has been growing at an exciting pace in recent years. The interdisciplinary nature of both micro-machining techniques and their applications can and does lead to exciting synergies. This course will explore the world of mostly silicon-based micro-machined transducers, i.e., micro-sensors and micro-actuators. This requires an awareness of material properties, fabrication technologies, basic structural mechanics, sensing and actuation principles, circuit and system issues, packaging, calibration, and testing. The material will be covered through a combination of lectures, case studies, individual homework assignments, and design projects carried out in teams.

ENG ME 305 (Zhang)
Mechanics of Materials
Definitions of stress and strain. Stress and strain transformations. Stress-strain-temperature equations. Yield criteria for ductile metals. Fatigue failure. Torsion of shafts and thin-walled tubes. Bending of beams. Combined loadings. Elastic stability and column buckling. Includes laboratory exercises.



Professor Shyam Erramilli and his graduate students conduct research in their lab.

Photonics Center Dean's Fellowship Program

The Photonics Center Dean's Fellowship program aligns with the standard Dean's Fellowship program supported by the Graduate School of Arts and Sciences (GRS) and the College of Engineering. Below are the requirements for fellowship candidates:

Fellowship Candidates must be from Photonics Center affiliated departments:

Graduate School of Arts and Sciences (GRS):
- Physics
- Chemistry
- Astronomy/Space Physics

College of Engineering (ENG):
- Biomedical Engineering
- Electrical and Computer Engineering
- Mechanical Engineering
- Materials Science Engineering Division

School of Medicine:
- Microbiology
- Psychiatry

Photonics Center Dean's Fellowships require research alignment with Photonics Center faculty members. Graduate applications must identify:
- Interest in working with a Photonics Center faculty member or group.
- Interest in specific graduate research topics in photonics.

Responsibilities of Photonics Center Dean's Fellowship recipients include:
- Completing at least one rotation or research program in a Photonics Center faculty laboratory.
- Participating in Photonics Center community activities.

The Photonics Center did not receive any acceptances for the number of Dean's Fellowships that were offered this year.

Science and Engineering Day

On March 21, 2012, Boston University hosted its annual Science and Engineering Day event. This event is held annually in the George Sherman Union and gives students from all science and engineering disciplines the opportunity to share their current research. Each year, the Photonics Center sponsors a prize for this event, the Herbert J. Berman "Future of Light" Award.

The Photonics Center would like to congratulate the following individuals who won awards at this year's event:

Photonics Center Berman Future of Light Prize
Winner: Andrew Fisher
Advisor: Lee Goldstein
Title: Modelling and Elucidating the Pathobiology of Blast-induced Traumatic Brain Injury in the Mouse

ENG Dean's Award
Winner: Alp Artar
Advisor: Hatice Altug
Title: Multispectral Fano Resonances in Hybridized Metamaterials

Center for Nanoscience & Nanobiotechnology Award
Winner: Arid Cetin
Advisor: Hatice Altug
Title: Plasmon Induced Transparency with Asymmetric Pi-Shaped Metamaterials

CELEST/CompNet Award
Winner: Schuyler Eldridge
Advisor: Ajay Joshi
Title: Biologically-inspired Hardware for Autonomous Robots

President's Award
Winner: Else Frohlich
Advisor: Xin Zhang
Title: The Use of Controlled Surface Topography and Flow-induced Shear Stress to Influence Renal Epithelial Cell Function

Teachers (RET) in Biophotonic Sensors and Systems

Professor Emeritus Michael Ruane (PI), Cynthia Brossman (co-PI) and Helen Fawcett (co-PI) completed the second year of a three-year NSF RET. During this session, five teacher teams were paired (middle school with a high school teacher, or pre-service with a high school teacher) and worked together on hands-on research projects. The faculty members who mentored these teachers included Professors Bennett Goldberg, Xue Han, Selim Unlu, Bjoern Reinhard and John Connor. In addition to working in the laboratories, the 10 teachers participated in weekly pedagogy sessions, including one through the Smart Lighting Engineering Research Center. The teachers also split into two groups to participate in cleanroom activities, where they worked on photolithography equipment in the Class 100 cleanroom to spin wafers, expose them with a mask, and develop the final wafers.

2011 Faculty Projects	2011 RET Teams	School
In-Vivo Han	Mary Beth Oldham	Norwood Senior High School
	Jessica Leach	Quincy High School (Pre-Service)
In-Vivo Unlu	Bryan Jonsson	City on a HIll Charter Public High School
	Jared Quinn	Overlook Middle School
Resonant Interferometric-Connor	David Bennett	The English High School
	Valentina Sountsova	Bancroft School
Resonant Interferometric-Goldberg	Ken Altshuler	Wayland High School
	Jessica Long	Pre-Service
Point of Care - Reinhard	Marvin Guitierrez	English High School
	Ned Dawes, Jr.	Marblehead Veterans Middle School

RET David Bennett works in Hatice Altug's laboratory preparing samples for surface chemistry and antibody attachment as part of John Connor's program (left). Martin Gutierrez, works in Bjoern Reinhard's laboratory to evaluate an incubated photonic chip from his research project (right).

More information about the projects and the teachers can be found at http://www.bu.edu/lernet/ret/index.html.

Boston Urban Fellows Project

Professor Bennett Goldberg continued work as principal investigator this year with the Boston Urban Fellows Project. The Boston University Urban Fellows Project is a 10-year NSF supported program to institute a sustainable model of immersing K-12 teaching partnerships within urban school systems for graduate fellows in sciences and engineering.

This project has further strengthened the existing relationships between Boston University and the Chelsea, Quincy, and Boston urban school districts. The Boston Urban Fellows Project has trained 73 K-12 fellows in urban schools and worked with more than 200 classrooms since it was established seven years ago.

This year, four students were coached for the state science fair, completing experimental work with lobsters. Two students competed in the state science fair, where their project was one of only five other projects from Boston Public to receive state-level awards. This group received an honorable mention at the state science fair.

The project's support staff provides content support, curriculum materials, and role models for more than 5,000 children.

OSA and SPIE Student Chapters

During Fall 2011-Spring 2012, the OSA/SPIE chapter was led by the following officers:

President: Katherine Calabro
Vice President: Alket Mertiri
Secretary: Xirui Zhang
Treasurer: Ronen Adato
Additional Officers: Durba Chaudhuri and Christopher Hwang

The OSA/SPIE chapter organized and held four events:

1) Family Optics Day (September 17, 2011): As a way to extend the reach of optics education to a larger and more diverse audience, the OSA student chapter held a 'family optics day.' The outreach event was organized in a manner similar to a science fair, with participants being free to roam between a dozen demonstration stations, each focused on a different area of optics. The event was publicized throughout the Boston area, drawing an attendance close to 300 people.

2) General Meeting and Elections (October 17, 2011): All students (predominantly graduate students) in the Photonics Center were invited to attend a general meeting and election for the chapter. Pizza was provided. At the meeting, events from the previous year were discussed, officers were elected for the coming year, and potential future events were presented.

3) Professional Development Series (February 24, 2012): Tom Tague from Bruker Scientific came to BU to give a presentation on the use of the FTIR equipment in the 5th floor shared Integrated Optics Laboratory.

4) Industry Networking Night (March 20, 2012): In collaboration with the New England Section of the OSA, a networking event was held at BU during which students had the opportunity to meet and network with local professionals in the Boston area optics industry. The format involved several short presentations from select professional attendees during a light dinner.

Boston University Satellite for Applications and Student Training (BUSAT2): A New Beginning

The BUSAT2 team completed a University Nanosat Program (UNP) Critical Design Review (CDR) for a USAF review panel at Boston University on April 3, 2012. As a result of this review the mission of the BUSAT2 satellite has been shifted to focus on the task of easily incorporating multiple payloads into a single satellite. One group of these payloads will have a space weather scientific mission. Instruments in this group will perform measurements of the precipitating energetic electron fluxes from low Earth orbit over the high latitude auroral zones and simultaneously image auroral emissions caused by these electrons. Additional payloads are being provided by New Mexico Institute of Mining and Technology to measure the thermal plasma environment around the satellite as well as the structural health of internal components.

The BUSAT2 team has also had separate proposals accepted by NASA to test portions of the BUSAT2 hardware, first, on a very high altitude balloon flight (the HASP program) and second, with the NASA Flight Opportunities "zero G" parabolic flight program where the team will test the proposed BUSAT2 solar panel and antenna deployment mechanism. These flights will occur in August 2012 along with another UNP project review, the Proto-Qualification Review (PQR) in Logan, Utah. The summer team for this year includes 18 BU students, most of whom are being paid for a 10-week summer effort from funding provided by a number of administrative centers at BU. The seventh cycle of the University Nanosat Program (NS-7) involves 10 competing universities, which have two years to develop a functioning satellite that will be judged by the US Air Force in January 2013 to determine a winner. The winning satellite will then be flown by the US Air Force after an additional two years of flight fabrication, testing, and qualification. A satellite ground station has been installed on the roof of the Photonics Building to permit the command and control of the satellite on-orbit and mission communications.

Facilities and Equipment

The Boston University Photonics Center opened in June 1997 and consists of ten floors of 235,000 net square feet of space including: classrooms, conference rooms, faculty offices, educational laboratories, faculty research laboratories and three shared laboratories managed by the Photonics Center.

The Center's faculty, students, and incubator companies utilize these core-shared facilities. The Photonics Center also offers collaborators from industry and other universities use of the facilities when time is available. Upgrades are routinely made to the three-shared laboratories to ensure faculty and student research is being supported and maintained.

The Photonics Center also features a Business Innovation Center located on the 6th floor. The Innovation Center consists of 15,000 square feet of flexible space that can sponsor up to 14 start-up companies. The space provides state-of-the-art facilities and a collaborative environment with faculty and students.

New and existing Photonics Center faculty members are provided with Photonics staff assistance in laboratory design. This year, Professors David Bishop and Xin Zhang moved into their newly designed and/or redesigned laboratories in the Photonics Center.

Shared Laboratory Facilities

The Optoelectronic Processing Facility (OPF) includes a Class 100 photolithography cleanroom and a Class 1000 cleanroom with processing and test equipment for die and wafer level processing. The Integrated Optics Laboratory (IOL) includes a flip chip bonding system in the Class 100 cleanroom and a standard laboratory space next door for spectroscopy measurements. The Precision Measurement laboratory (PML) consists of two laboratory spaces with scanning electronic and atomic force microscopy among other analytical surface characterization tools.

Optoelectronic Processing Facility (OPF)

OPF is a multi-user 2500 sq. ft. facility located on the 8th floor of the Photonics Center. The facility contains equipment for semiconductor and optoelectronic fabrication from bare chip to fully populated components. The facility includes both Class 100 and 1000 cleanrooms and equipment facilitating photolithography, wet chemical processing, thin film depositions, plasma etching and cleaning, thermal oxidation, thermal annealing, wire bonding, and electrical characterization.

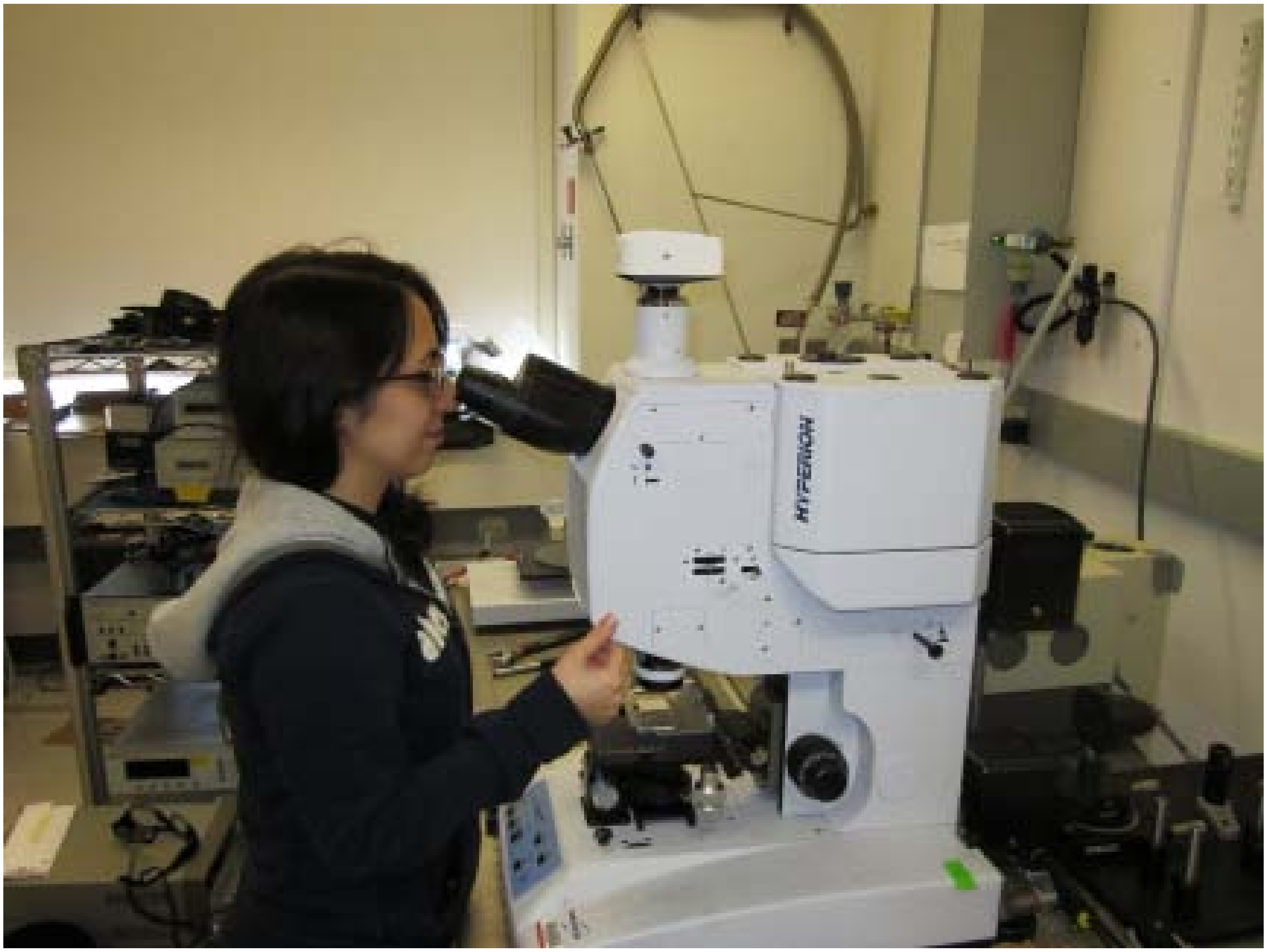
The Class 100 cleanroom is a photolithography and mask-making laboratory. Two types of photoresist spinners are available for use by all self-users in OPF. The standard Headway Research spinner is designed to accommodate small chip level 5mmx5mm to six inch wafers, while the Suss Microtech Delta 80 is used to spin chrome on glass masters that can be written using the Heidelberg Direct Write Laser System. The laboratory conveniently provides ovens and a hood for bakes to facilitate development. Chip and wafer exposure is achieved through two UV exposure tools; the MJB3 (for three inch masks or smaller) and the MA6 (up to a 6 inch square masks). A high-powered optical Nikon microscope provides higher resolution imaging for surface inspection.

Cleaning, etching or characterization is included in the Class 1000 cleanroom through wafer processing from the photolithography room. With a Tencor surface profilometer, students learn how to measure the step height of features that they make on wafers. This contact profilometer requires students to either create measurement fiducials on their structure or work with large features into which the stylus can drop down, reach base surface, and then run back up to the top of the structure. The high powered optical Nikon microscope allows users to captures still or video images from the sample or wafer.

Dry etching processes are readily available and used in the OPF cleanroom, including plasma etching, reactive ion etching and a deep reactive ion etching. In addition to dry etching, both acid and separate solvent hoods are available to complete wet chemical etching or cleaning. In addition, the HF vapor etch systems has addressed safety issues for students or faculty so that they do not have to handle liquid HF, but rather use the vapor system to release oxide films. This system accommodates small pieces of wafers as well as four and six-inch full wafers.

A majority of the research laboratories at Boston University use thin film deposition systems. Thermal oxide furnaces, evaporators and sputtering systems all provide students with the ability to learn about different coating processing methodologies and how to measure the films deposited after processing. Wire bonding, wedge bonding, or testing can also be done inside the cleanroom in OPF. The Current Voltage/Capacitance Voltage characterization test set up is used to evaluate devices post wire bonding and pre-integration into test set ups on the lab bench.

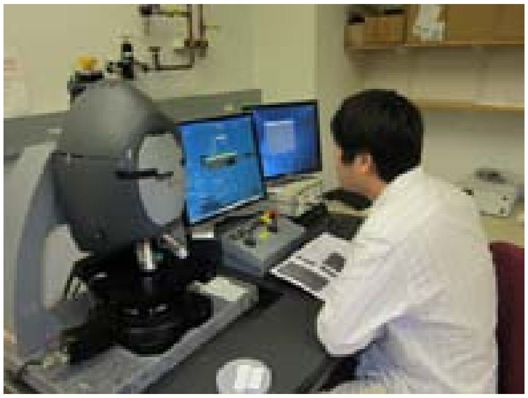
Integrated Optics Laboratory (IOL)



The IOL houses a Class 100 cleanroom and a standard laboratory space within its 900 sq. ft. It is a multi-user facility on the 5th floor of the Center and is stocked with state-of-the-art equipment for bonding and spectroscopic analysis of components.

The Class 100 cleanroom employs a Suss Microtech FC-150 flip chip bonder which is used to seal and create eutectic bonds either through thermocompression or soldering processes. This is a precise system that uses fiducials to aid in placement accuracy. Several researchers in device packaging (LED's) use this piece of equipment and outside collaborators also use the system for alignment and bonding of devices.

The IOL standard laboratory space includes a soft lithography area and spectroscopic tools. The soft lithography station uses PDMS to make replicas from masters created through photolithography or e-beam writing. The Varian Cary 5000 UV-VIS-NR spectrometer covers wavelength ranges from 175-3300 nm. In addition to measuring reflectance and transmission at a particular wavelength, it can also measure absorption.



Precision Measurement Laboratory (PML)

PML is comprised of two laboratories located in the basement of the Photonics Center. The PML allows the measurement of features and surface morphology. In one of the lab spaces, a JEOL SEM with imaging, Cathodoluminescence (CL), and Energy Dispersive Spectrometer (EDS) is available for use. The EDS allows validation of elemental composition and surface contaminants in selected locations over the surface of the sample. The Cathodoluminescence (CL) monochromator allows the detection of energy released in the visible spectrum from electrons in an atom returning to their original energy level after being excited by the bombardment of electrons from the e-beam in the SEM. From the spectrum, elements within the sample can also be determined and emission spectrum can be evaluated. CL spectra provide information about wavelength of the emitted light at areas of interests (dislocations, grain boundaries, lattice imperfections). CL maps provide information about spatial distribution of light and defects in the specimen.

The second laboratory space includes: a Veeco (formerly Digital Instruments) Atomic Force Microscope (AFM) a Pico-Force AFM System, a Zeiss Supra 40VP Field Emission Scanning Electron Microscope (FESEM), a Zygo NewView 6300 and a Zeiss Supra 55VP FESEM. The AFM was upgraded previously with a closed-loop x-y scanner. This assisted in nanoscale structural measurements. The Pico-Force AFM System enables accurate force measurements and manipulation of biological or material samples at the pico-Newton level, including inter- and intramolecular forces, for applications ranging from drug discovery to basic molecular-scale research. The Zeiss Supra 40VP FESEM allows polymers and plastics to be viewed without conductive coatings, thus a non-destructive way to view a sample. The ebeam blanker added to the Zeiss Supra 40VP FESEM for the exclusive use of Photonics members allows e-beam writing of nanoscale structures. The ZYGO NewView 6300 with dynamic MEM's capability also has a heating and cooling stage that allows testing under controlled temperature and the viewing and measurement in-situ. Surface roughness, morphology, and displacement can all be measured using this instrument.

Last year's capital equipment purchase was a Zeiss Supra 55VP FESEM. In addition to imaging using secondary electron detectors, this SEM is also capable of imaging thin TEM samples using a STEM detector, providing atomic contrast information using a backscattered electron detector and chemical composition using EDS (Energy Dispersive Spectrometer). It is also equipped with an EBSD (Electron Backscatter Diffraction) detector which gives information on the crystalline structure and grain boundary orientations on polished materials. A hot and cold stage is also available for in-situ work in the SEM chamber.

Equipment Committee

This year's capital equipment purchase fulfilled an emerging need, identified in a poll of faculty members, to enable further research in nanofabrication. There was overwhelming support for the addition of an e-beam system to the Zeiss Supra 55VP FESEM. This system was added to allow a backup to the existing, Supra 40VP so that if the system went down, it would not require users to stop their research. The following criterion was considered in making the decision to support the new equipment purchase:

- The instrument will be widely usable as a shared resource in the Photonics Center to enhance the research and development programs.
- The new instrument will provide critical leverage for attracting additional support to the Center for research and development.
- The instrument will enhance the careers and photonics-related research of junior faculty members of the Photonics Center.
- The existing instrument is near full usage and more users are coming on-line.

Using these guidelines for identification and ranking of equipment improvements, the majority of Photonics faculty users supported the purchase of an additional e-beam add-on to the newly installed Supra 55VP. The e-beam system was installed on the Supra 55VP and includes RAITH electronics, a beam blanker and other necessary components.

Zeiss Supra 55VP FESEM

Innovation Center Facilities

Located on the 6th floor of the Photonics Center building, Boston University's Business Innovation Center currently hosts 11 technology start-up companies. There is a healthy turnover in the Innovation Center space with five companies departing over the past year and seven new companies joining the Center. The mix of companies includes: life sciences, biotechnology, medical devices, photonics, clean energy and engineering. Currently four of the companies originate from within BU and the other six from outside of BU. All companies are engaged in the commercialization of new technologies of importance to society and all are engaged in BU's educational mission to train students in entrepreneurial management.

Companies in the Center, which originate externally to BU, are held to the highest professional standards in the market space they serve. They represent the benchmark by which BU internal spinout companies may be compared and act as exemplary living case studies for the teaching of entrepreneurship to our students. All are professionally managed by seasoned and credentialed CEO's and founders and funded by reputable institutional investors. All have undergone external professional due diligence by their investors. All are commercializing revolutionary technologies developed at many of the region's leading research institutions such as: Dana-Farber Cancer Institute, Massachusetts General Hospital, Draper Laboratories, MIT and other universities and government agencies.

Total financing for all the companies in the Business Innovation Center is approximately $35 million, mostly from established venture capital funds. During FY12, two companies (Springleaf Therapeutics and MTPV) received series B financing. Additionally, ByteLight received Angel funding as they exited the Center. About 70 employees work with the incubator companies on the Charles River Campus. In total, this represents a substantial concentration of entrepreneurial business activity on the Boston University campus.

In 2006, we began partnering students with incubator companies. Since that time, approximately 70 BU students have worked directly with incubator companies as interns. The Institute of Technology Entrepreneurship and Commercialization (ITEC) in the Graduate School of Management has provided student interns through numerous entrepreneurial programs while other students have come from the College of Engineering. To date, incubator companies have hired two Ph.D. students full time. In addition, ITEC is currently supporting four new student startup companies that entered the incubator this year: Applified, Wanderlu, JLP and TR Aeronautics.

Companies That Exited During July 2011– June 2012

Company Name	External Origin	Technology	Market Sector	Funding
ByteLight	Student Start-up	Receivers for Intelligent Lighting Systems	Energy, Lighting	Angel
CoSMO Systems	Individual Research	Software for Predictive Modeling	Healthcare, Energy	Bootstrap
Cyber Materials	BU, Manufacturing Engineering	Process Control Thin Film Deposition	Industrial Manufacturing	SBIR, Sales
mobiLIFE	Student Start-up	Buletooth CGM	Healthcare, Medical Devices	Bootstrap
Zipcents	Student Start-up	Software Algorithms for Secure On-line Payment	On-Line Financial Transactions	Bootstrap

Current Incubator Companies

Company Name	External Origin	Technology	Market Sector	Funding
1087 Systems	Unique Development	Cellular Measurement Platform	Healthcare	Bootstrap
Applified	Student Start-up	Gaming Software	Social Networking	Bootstrap
Block MEMS	Company Spin-Out Block Engineering	Optical MEMS Micro Chemical Sensors	Military, Industrial	DoD, Corporate
Clean Tech Open	Silicon Valley Volunteers	Entrepreneurship and Social Networking	Clean Technology	Donations/Grants
J2P	Student Start-up	Consulting Management	Technology Promotion	Bootstrap
Mass Medical Devices Journal	De Novo Start-up	N/A	Medical Device Journalism	Sales/Advertising
MTPV	Draper Laboratories	Microgap Thermo Photo Voltaics	Clean Energy	Angel
Nano Surfaces	Cornell University	Nano Structured Surfaces	Anitfouling Coatings	Angel
Spring Leaf Therapeutics (formerly Entra Pharmaceuticals)	MIT	Microelectronics	Drug Delivery	Venture Capital
TR Aeronautics	Student Start-up	Optical Imaging	Aerial Surveillance	Bootstrap
Wanderu	Student Start-up	Search Software	On-line Business Transactions	Bootstrap

Building Projects

Construction on the sixth floor of the Photonics Center began in the Fall of 2011 in preparation for Professor David Bishop's office space, laboratory and shared materials science core facility.

PHO 609

The project entailed converting original incubator office space into a faculty office and conference room as well as an outer graduate student and post-doctoral researcher space allowing seating for up to six students and researchers.

PHO 607

This project including converting original incubator office space into laboratory space including laboratory exhaust. The laboratory was designed specifically for Professor Bishop's research into materials including carbon nanotubes, MEMS devices and general materials research such as coatings and growth.

PHO 603 and 605

These two laboratory spaces have been designed to be an open floor plan materials science core laboratory. Within the laboratory are acid and solvent hoods, microscopy areas and general stations set up to accommodate exhaust, facilities, and other requirements depending on the equipment to be assigned to that station. The latest addition to the laboratory is an Inverted Fluorescent Microscope/AFM.

PHO 903

Construction in PHO 903 was completed at the end of May 2012. As Professor Xin Zhang's collaboration on the medical campus is increasing, the need for a BL2 and laser space became evident. The Photonics Center has reconfigured the former Photonics Center general laboratory into a Class IIIb/IV laser facility with BL2 room. An inner room was finished and an incubator and biosafety cabinet that Professor Zhang had in her previous location were moved into the room. An acid and base hood were installed along with a general wet chemistry area and general mechanical assembly areas. An additional laser bay was added and the dark room remained intact with some additional facilities added in that room.

Community Events

The community within the Photonics Center spans several colleges and schools on both Boston University campuses. As the community expands, the role of community events and outreach becomes even more important to further the center's collaborative mission.

The Photonics Center collaborates each year with outside academic institutions, industrial partners and to the greater BU Community through symposia, seminars and building activities. These events foster interdisciplinary discussion and encourage faculty and students to collaborate with a variety of professionals on fundamental research.

Photonics Cafes and Forums

The Photonics Center hosted two monthly events: The Photonics Cafe and the Photonics Forum. The cafes bring together the faculty, students, staff and incubator company employees in an informal setting for conversation and collaboration. The cafes are hosted on the second Friday of each month from September through April in the West End Lounge.

The Photonics Forum, held on the fourth Wednesday of each month throughout the Spring of 2012, give the community opportunities to participate in technical discussions in an open forum over lunch. A Photonics Faculty member is selected to discuss their current research endeavors and the real-world applications of their research.

2012 Forum Schedule

January
Presenter: Igor Bratnikov and Ryan Hunter
Presentation: Entrepreneurship at the Photonics Center

February
Presenter: Boston University Environmental Health and Safety
Presentation: Annual Laboratory Safety Training

March
Presenter: John Kurkomelis, Boston University Radiation Specialist
Presentation: Annual Laser Safety Training

April
Presenter: Professor Xin Chen
Presentation: Applications of Vibrational Sum-frequency Spectroscopy in Soft Materials Science

May
Presenter: Professor David Bishop
Presentation: Silicon Micromachines for Science and Technology

15th Annual Future of Light Symposium: Neurophotonics: Optogenetics and Imaging

This year, the 15th Annual Future of Light Symposium focused on neurophotonics: optogenetics and imaging. Over 200 people from Boston University, outside academic institutions and industry attended the event.

The agenda for this year's symposium featured presentations by Photonics faculty members and researchers from leading photonics research institutions. The conference explored leading edge research in the emerging field of neurophotonics, where light based systems are used to study, control, and image neurons and neural circuits.

Our speakers included:

Peter Bergethon, Boston University School of Medicine
Ed Boyden, MIT
Adam Cohen, Harvard University
Florian Engert, Harvard University
Alan Horsager, EOS Neuroscience Inc.
Jerome Mertz, Boston University
Orian Shirihai, Boston University
John Spudich, University of Texas-Houston Medical School

The symposium also included a lunch speaker, Chris Nowinski from the Sports Legacy Institute.

At the conclusion of this year's conference, a poster session was held for graduate students, post-doctoral researchers, and research staff members where they had an opportunity to present their current investigations. Thirty-four posters were submitted to the poster session. The poster session gives outside guests the opportunity to gain further insight into the Center's education and research missions by giving students and researchers the opportunity to share their results.

Spring Cleaning Day 2012

The Boston University Photonics Center, Electrical and Computer Engineering Department and the Environmental Health and Safety Department hosted Laboratory Spring Cleaning Day on April 5, 2012.

In addition to learning about safety, the students, faculty, researchers, and staff enjoyed breakfast and a Ben & Jerry's ice cream party. Red Photonics Center hats were handed out as a give-away. BU Sustainability set up a table to answer questions about their program at BU, and to provide the opportunity to sign up for office audits to determine the "greenness" of each office.

A variety of gift cards were handed out to the winners of the prizes listed below.

This year's winners included:

Most Improved – Altug Laboratory ($100)

Most Team Work – Erramilli Laboratory ($50)

Most Sparkling – Reinhard Laboratory ($25)

Photonics Center Guest Speakers

Over the year, the Boston University Photonics Center hosted several seminars by photonics experts. The following list includes the seminars for 2011–2012.

August
Presenter: Professor Brian Cunningham from University Illinois at Urbana-Champaign
Title of Presentation: Getting Molecules to "See the Light": Nanostructures and Instruments for Biomedical Detection

November
Presenter: Professor Andrea Armani from the University of Southern California
Title of Presentation: Integrated Photonics for Exploring Biological Systems

Presenter: Professor Sylvain Gigan from ESPCI ParisTech
Title of Presentation: Controlling Light in Complex Media: A Tool for Imaging and for Fundamental Investigations

December
Presenter: Professor Jason Fleischer from Princeton University
Title of Presentation: A Brief Introduction to Computational Imaging

January
Presenter: Professor Jonathan Klamkin from Scuola Superiore Sant'Anna,
Title of Presentation: Photonic Integrated Devices, Circuits, and Subsystems

February
Presenter: Dr. Elison Matioli from the Massachusetts Institute of Technology
Title of Presentation: Nanophotonics for Energy Efficiency Applications: Exploiting Light Emitters Up to the Last Photon

Presenter: Dr. Michelle Sander from the Massachusetts Institute of Technology
Title of Presentation: Towards Integrated On-Chip Femtosecond Photonic Technology

Presenter: Dr. Nanfang Yu from Harvard University
Title of Presentation: Molding Optical Wavefronts Using Meta-Interfaces

Presenter: Dr. Simone Gambini from University of California, Berkeley
Title of Presentation: Electronics for Future Medical Devices: From Connected Implants to Point of Care Diagnostics

March
Presenter: Ted Sargent of the University of Toronto
Title of Presentation: Optoelectronics Using Solution-Processed Colloidal Quantum Dots

Presenter: Dr. Alexey Gorshkov from the California Institute of Technology
Title of Presentation: Many-Body Physics with Atomic, Molecular, and Optical Systems and Methods

Presenter: Dr. Ingmar Hartl from IMRA America, Inc.
Title of Presentation: Frequency Comb Spectroscopy: From Precision Metrology to Hyperspectral Imaging

Photonics Center Guest Speakers (cont'd)

March (cont'd)
Presenter: Dr. Laura Waller from Princeton University
Title of Presentation: Computational Wave-Field Imaging

April
Presenter: Dr. Bruce Macintosh from Lawrence Livermore National Laboratory
Title of Presentation: The Gemini Planet Imager and the Optical Science of Imaging Extrasolar Planets

Presenter: Dr. Charles Tu from the University of California, San Diego
Title of Presentation: Envisioning a Bright Future for MBE Research

May
Presenter: Dr. Richard Paxman from General Dynamics Advanced Information Systems
Title of Presentation: Wavefront Sensing and Imaging With Phase Diversity

Presenter: Professor Vahid Sandoghdar from the University of Erlangen
Title of Presentation: Ultrasensitive Detection and Tracking of Nano-Objects via Scattering Interferometry

June
Presenter: Professor Ayman Abouraddy from the University of Central Florida
Title of Presentation: Multi-Material Fibers: Prospects for Photonics and Nanotechnology

August
Presenter: Professor Hakan Urey from Koc University
Title of Presentation: Optical MEMS Sensors and Actuators for Displays, Spectroscopy, and Biosensing

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