PRIDE: Photonics Research in Interdisciplinary Education

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Abstract

A new combined research-curriculum development (CRCD) program at Boston University titled Photonics Research in Interdisciplinary Education (PRIDE) is described. The PRIDE program is designed to demonstrate vertically integrated curriculum development by incorporating three levels of modules into a wide range of existing courses. Examples of photonics research and knowledge are molded into modules to enrich standard core, specialized elective and design courses of undergraduate and early graduate curricula. An interdisciplinary faculty team has been formed to develop integrative learning experiences focusing on modern research in photonics as an important and interesting problem area. Modules are based on and demonstrated by recent photonics research, including photonic materials and devices, optical data storage, optical communications, displays and photonics systems. Self-contained *applications modules* integrate engineering concepts in upper division core. *Laboratory practicums* provide empirical experiences to supplement photonics electives. Finally, open-ended *design cases* pose capstone photonics design challenges for teams of students. Our modular implementation of photonics into existing courses represents a significant depart ure from standard curricular development. This approach reduces the barriers to entry for cross-disciplinary education, is inherently transportable while maintaining local flexibility of content, and incorporates photonics research into a wide range of different curricular t epics.

I. Introduction

Photonics has many characteristics that make it appropriate for curriculum development. Photonics is important to national competitiveness, offers exciting technical challenges, is neglected in the existing curriculum, and presents a paradigm to address educational challenges in the training of engineers and scientists. Photonics stands where the semiconductor industry was in the late 60's – entering a time of rapid growth, with broad impacts for society and the economy. The Optoelectronics Industry Development Association (OIDA) released a report[1] detailing that "industry sectors enabled by optoelectronics will grow from approximately $75 billion worldwide today, to more than $230 billion within the next decade, to over $400 billion in twenty years (in constant dollars). The number of jobs worldwide dependent on optoelectronics is expected to grow from several hundred thousand to several million. This is due both to the growth in the overall electronics markets and the expanding role of optoelectronics within the electronics industry." The report documents that the U. S. is currently lagging in many critical areas of the photonics market explosion. The OIDA report is only a recent echo of concerns first widely stated in 1988 by the National Research Council (NRC).2 The theme of the NRC report is that photonics technology is a market rapidly being ceded to our international competitors. The 1991 report of the National Critical Technologies Panel[3] states: "advances in electronic and photonic materials will set the pace of technological progress in communications, image processing and information processing - key sectors for both civilian economy and national security. The main challenge is to develop materials that effectively integrate electronics and photonics to achieve dramatic improvements in systems performance, reliability, and cost ."

A. Technological Challenge

The photonics industry is increasingly characterized by rapid transfer of technological innovation from the research laboratory to the marketplace, Much of this is a competitive necessity, driven by worldwide markets in communicant ions, computing, and medical services. Breakthroughs in photonic devices typically show up in consumer products in a few short years. Some innovations, like infrared personal i dent ificat ion beacons (extensively used to protect friendly troops in the battlefield confusion of the Gulf War) were conceived, protot yped, and manufactured in quantity in a few months.

To succeed in such an environment, R&D professionals must be able to work across the entire development cycle. This includes applying fundamental science at the materials level, coordinating device level constraints to implement products and services in an efficient and economic manner, and anticipating systems level requirements from manufacturing to end-users. Training for such careers must similarly reflect the complexity and interactions found in real problem cent exts.

Since warning calls were issued nearly a decade ago, why have we continued to fall behind in our photonics competitiveness, and why do our curricula still lack any significant photonics component? There are several contributing factors. Transitions to new technological areas take time as faculty and facilities must be assembled. Students must be convinced that new areas will be productive and offer attractive professional opportunities. Funding sources, in both government and industry, must become convinced that action is needed, and then implement programs to support new initiatives. Finally, cross-disciplinary concentrations like photonics have been poorly served by traditional, compartmentalized curricular struc-t ures.

There have been significant recent institutional initiatives in response to the need in photonics. NSF centers of excellence related to photonics have been established at several universities, e.g., University of -Illinois, University of Colorado, University of Texas, and Carnegie Mellon. Traditional programs at University of Rochester and University of Arizona have been expanded with government and industry support. Industry organizations like OSA, OIDA, SPIE, and IEEE/Lasers and Electro-Optics Society have enjoyed growth. But in most academic institutions, the change has been small, and localized, and strongly content-oriented, as evidenced by a review of the Optical Society of America *Annual Guide to Photonics Programs*,[4] or the SPIE *Optics Education*.[5]

B. A Paradigm for Integrative Engineering

Photonics is a paradigm for the technological challenges to national competitiveness that today's engineers and scientists must be prepared to face. The field developed relatively rapidly, has profound impacts in many applications, and draws on many areas of knowledge. Successful competition in photonics technology therefore requires an integrative set of skills. Engineers must synthesize traditional engineering knowledge (e.g. electronics, controls, signals and systems, electromagnetic, and materials) with broad understanding in related fields such as lasers, solid-state physics, optoelectronics, and fiber-optics. Industrial and university research advances in these areas need to be rapidly incorporated into the engineer's training to provide the necessary educational breadth, and to meet the projected demands for engineers and scientists in photonics. The engineering student must learn not only the knowledge base of photonics, but also the skills to integrate and synthesize that knowledge.

There is an undeniable need for courses, textbooks, instructional modules and laboratories, and design experiences. Rarely is photonics found in undergraduate engineering or physics courses or textbooks, despite immense student interest, compatibility with fundamental skills, and relatively good accessibility to the novice. Engineering is replete with other technologies that once were taught only in research-oriented seminars and are now fundamental knowledge. Just as transistors gradually replaced tubes in the curricula, photonics is ready to enter the curriculum, from core courses to design projects. To respond to the need and the challenge in photonics education a new combined research-curriculum development (CRCD) program at Boston University – Photonics Research in Interdisciplinary Education (PRIDE) – has been initiated.

II. Objectives and Scope of PRIDE at Boston University

The general objective of the PRIDE program is to incorporate exciting research advances in important photonics technology into the undergraduate and early graduate curriculum. The PRIDE program will provide integrative curricular modules to bring photonics from the world of research to undergraduate core courses, to elective course laboratories, and to our capstone design course. Our focus is on advanced undergraduate experiences, but early graduate curricula overlap through the specialized electives, and would also be served. Integrating photonics modules into existing curricula, rather than building specialized courses, will demonstrate a different model of curriculum development. Facult y researchers and research professors, too busy to build an entire course, will be stimulated to offer their research expertise in smaller, more manageable and focused photonics modules. Faculty lecturers will welcome these new additions, suitably self-contained and illustrative of course materials, for their timeliness and high motivational appeal to students.

A. Modular Approach

PRIDE incorporates real-world research, presented by researchers, those faculty and industry partners who are actually working in the labs of the Boston University. These researchers will serve as guest lecturers, consultants, guides, or design project "customers." Our modular approach allows faculty to become involved at a manageable level, attracting a wider range of researchers photonics research facilities will be integral to learning and accessible to students for demonstrations, student experiments and specific training. It is an interdisciplinary program through the diverse training, interests and research areas of its faculty. Integrative problems necessarily draw upon multiple disciplines, even as they maybe concentrating on a few concepts, a particular laboratory, or a specific design problem.

PRIDE complements existing curricular efforts, both at Boston University and elsewhere. New and established courses benefit from an infusion at cross-disciplinary photonics content, thus developing a more effective integrated learning experience. The wide range of research-driven modules created in PRIDE will maximize the likelihood of inclusion at various levels into different types of curriculums. Finally, PRIDE presents a general curricular structure useful to many areas of research and education. We are developing *photonics applications modules* for the intermediate level courses, *instructional laboratory practicums* for the advanced electives, and *capstone design cases* for use in senior-level design and advanced lab courses each based on a real-world research result, process, or problem.

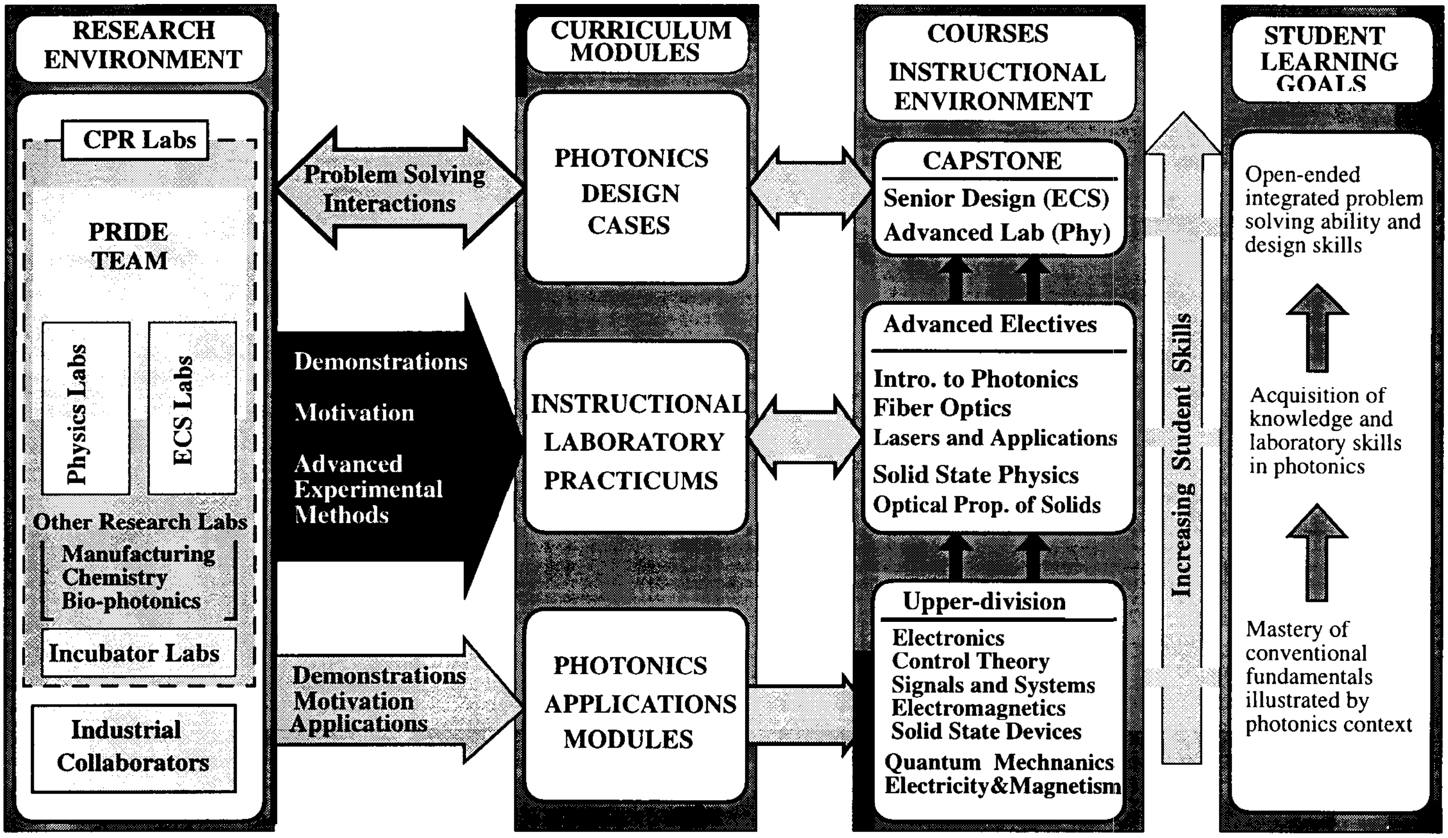

Figure 1: Schematic diagram of the relationships of research, new curriculum modules, and the instructional environment.

Figure 1 shows the relationships of research, new curriculum modules, and the instructional environment. The left-most arrows show an increased flow of research results, and more interaction with the research labs as more advanced modules are used. The next set of flows show that application modules are largely self contained in their contribution to upper-level undergraduate courses. Elective courses using laboratory practicums will see more information move from the classroom to the practicums and labs. Finally, the design cases will exhibit strong interaction with course knowledge and research activities. At the right, Figure 1 shows student learning goals for the modules. As students use more modules, they will develop more fundamental skills, advanced elective knowledge, and design skills in photonics.

1. Photonics Applications Modules

Modules are being developed for appropriate intermediate and upper division electrical engineering and physics courses. We are targeting electronics, signals, controls, electromagnetic, solid state materials, and quantum mechanics, but could also address communications or digital electronics. Preliminary discussions with course lead professors have indicated support for this effort.

Working in conjunction with the course lead professors, the project team identifies specific research problems that integrate and reinforce central learning objectives of the courses. At this undergraduate applications level, the principal learning objective is always within the existing course curriculum, and photonics is introduced to motivate, illustrate and elaborate on the fundamental course ideas and goals.

For example, in controls, the problem of temperature regulation of semiconductor communication lasers is chosen. In this research context, a photonics applications module would provide elements for incorporation into the controls course as a self-contained study unit (see Appendix). During implementation of the module, the researcher would address the class to present the introduction and discussion of the real-world implementation. A demonstration or visit to the researcher's lab would typically be included.

Other courses' application modules would follow slightly different formats, but each would include the general elements:

- introduction/context,
- modeling,
- design,
- evaluation,
- real-world solution and
- follow-up.

The written modules will be detailed and roughly equivalent to an extended textbook example, perhaps 10-15 pages in length with figures and equations. A resource section for the professor (instructions for the instructor) will provide references and a brief tutorial on the photonics principles involved.

2. Instructional Laboratory Practicums

Practicums, literally, the supervised *practical application of previously studied theory*, are being developed to supplement advanced photonics electives: Introduction to Photonics, Lasers, Solid State Physics, Optical Properties of Solids, and Fiber Optic Communications. The practicums are being developed in conjunction with the course instructors and with researchers working in related technical areas. They are organized around specific problems from our research labs or industry applications that require integration of course concepts to solve. The practicums introduce students to hands-on experimentation with relatively simple apparatus, leading into the more advanced laboratories and research projects of the design cases.

Each practicum is centered on a current research problem. For example, a practicum on photoluminescence for a technical elective on optical properties of solids could be based on the study of new materials in our Molecular Beam Epitaxy laboratory that exhibit luminescent lines that vary with excitation energy (see example in Appendix). All practicums share a common structure that begins with a research motivation, leads to relatively simple and inexpensive fundamental laboratory investigations, and culminates in advanced measurements and a discussion of research implications. Advanced measurements will occur in the research laboratories. Laboratory practicums will be detailed and organized similar to a journal experimental paper. Supplemental equipment and measurement process information will be given. Instructors will receive additional information on student and research lab apparatus. All the laboratory notes will be posted on a World Wide Web site with all the equipment specifications and background information hyperlinked to the laboratory manual pages.

3. Capstone Design Cases

In the capstone senior design project, students complete an open-ended group project with emphasis on oral, written, and technical engineering skills. Faculty, alumni, industry colleagues, and others serve as the students' 'customers", setting project requirements and helping to evaluate the students. Project requirements are negotiated in initial informal face-to-face meetings of customers and design teams. Eight to ten different projects are completed each semester. Appropriate research cases will be substituted for the physics advanced laboratory course.

Capstone design cases based on photonics research and applications are being prepared for use in the Electrical Engineering Senior Design Project and the Physics Advanced Laboratory. The cases present a '(customer" problem context whose required design

- incorporates fundamental and advanced photonics coursework,
- requires photonics modeling or measurements,
- provides a high level of challenge and encourage creativity, and
- admits a wide range of possible solutions.

The case materials given to the students mimic the successful case style used in fields like management and manufacturing engineering. A narrative description of the general problem and requirements are supplemented by quantitative data and specifications, some of which may be irrelevant or contradictory. Softer customer preferences will be described, and constraints elaborated (e.g. project budget, time limits, deliverables and delivery times, and facilities and equipment available).

Matched with the student case materials are instructor/customer materials. These provide additional background on the problem, clarify the data and specifications, identify likely decision points for the design team, and warn about obvious and subtle obstacles to success. A default minimal design will be described, although there is no "correct" design in such open-ended work. Evaluation criteria and expected resources needed will be included.

Cases are being organized around photonics research and current applications. Our intention is to have researchers serve as customers, to provide a realistic problem context, and to offer a skilled mentor to the design teams. A senior design project from Spring 1995 briefly illustrates the elements of a photonics design case in the Appendix.

III. Evaluation, Assessment, and Disseminate ion

Evaluation of this program will be conducted with both formative and summative components, using three distinct instruments: (1) an annual internal formative report by the curriculum team; (2) a second-year evaluation by an external panel; and (3) a summative study to evaluate the acceptance and effectiveness of our curricular modules.

A dedicated World Wide Web site (http: //phot on. bu. edu/PRIDE/) has been created for our course and curriculum development efforts. This site is linked to Engineering, Physics, and the Center for Photonics Research, to allow wide access to our efforts and to elicit suggestions from the wider community. Information on the new laboratory components including the description of individual experiments and laboratories, course materials, and written project reports by students will be posted on WWW. A workshop for educators will be organized in the last year of the program (1998) providing faculty training in the modules. Finally, we will offer on-site presentations in conjunction with some of the related Boston professional society meetings, e.g. SPIE, LEOS.

IV. Conclusions and Impact

We described the objectives and the structure of the new combined research-curriculum development (CRCD) program at Boston University - Photonics Research in Interdisciplinary Education (PRIDE). The PRIDE program targets creating three levels of photonics modules to enrich standard core, specialized elective, and design courses of the upper division undergraduate and early graduate curricula. Our modular implementation of into existing courses reduces the barriers to entry for cross-disciplinary education, is inherently transportable while maintaining local flexibility of content, and incorporates photonics research into a wide range of different curricular topics.

Curriculum development in PRIDE addresses photonics as an integrative problem context, and incorporates real-world research, presented by researchers, those faculty and industry partners who are actually working in the university research laboratories. Our modular approach allows faculty to become involved at a manageable level, attracting a wider range of researchers photonics research facilities will be integral to learning and accessible to students for demonstrations, student experiments and specific training. New and established courses will benefit from an infusion at cross-disciplinary photonics content, thus developing a more effective integrated learning experience. The wide range of research-driven modules created in PRIDE will maximize the likelihood of inclusion at various levels into different types of curriculums. Finally, PRIDE presents a general curricular structure useful to many areas of research and education.

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APPENDIX: Module Examples

Example: Photonics Applications Module – Temperature Control of Laser Diode
Research: Blue GaN Laser Development
Target Course: Control Systems

- *Introduction and motivation* (contextual problem statement, practical constraints). Describe the temperature dependence of lasers and typical performance goals. Discuss size, power, longevity and cost targets. Present physics and device structures of rear-facet detectors and thermo-electric cooling elements. Select a specific prototypical GaN laser configuration and temperature specifications .

- *Development of a model for control design* (analysis, modeling. Present data sheets for the devices and discuss nonlinearities, performance limits and tolerances. Make appropriate approximations to allow modeling and find theoretical or simulation models to describe system response to controls, e.g. thermal inertia.

- *Proposal of candidate controllers* (design). Using controls concepts such as error nulling, stability, pole placement, bandwidth, etc. choose controller parameters and implement with a choice of practical circuit components. Consider at least two candidates, e.g. controllers with different specifications for allowed maximum temperature excursions.

- *Evaluation of the candidates* (assessment, including ancillary effects). Analyze the candidates in terms of cost, parts count, manufacturability, reliability y and power consumption. Choose the final design of the temperature controller.

- *Discussion of practical implementation* (real-world solution, compromises that were made). Examine how the researchers solved the problem in their laboratory, and discuss the tradeoffs involved.

- *Follow-up topics* (to be pursued by interested faculty and students in more detail). Examples might include design of blue laser diodes for reduced temperature sensitivity, consideration of the rear-facet detector dynamics for pulse shaping control during temperature variations, and more advanced control designs, e.g. PID controllers.

Example: Instructional Laboratory Practicum – Excitation-dependent Photoluminescence
Research: Photoluminescence of dejects and band states
Target Course: Optical Properties of Solids (elective)

- *Introduction and motivation* (contextual research problem statement). PL measurements characterize the band structure and potential wavelength regime of novel materials, guiding fabrication of materials and devices. Tunable sources are in great demand for communications and data storage applications.

- *Fundamental instrumentation techniques* (learning the research methods). Excitation sources, sample dewars, and PC-controlled grating spectrometers will be presented. Data collection and analysis and experiment design would be explained. Lab safety with UV sources is stressed.

- *Instructional laboratory measurements* (applying the methods to standard materials). Students would measure PL on well-characterized samples, establish their measurement competency, and discuss equipment and operator safety issues.

- *Open-ended measurements on new materials* (conducted in Molecular Beam Epitaxy research lab). Students will measure research samples in the MBE laboratory's PL system, and obtain response curves under low and high power HeCd laser illumination.

- *Discussion of possible mechanisms* (insights into optical materials and research process). The researchers will propose how PL peaks could change relative magnitude as a function of excitation energy, and what is an appropriate physical interpretation. Implications for tunable sources, whose line shape would vary with pumping energy, would be discussed.

Example: Capstone Design Case Sailboat Optical Mast Alignment System

Research: Positioning, Tracking Methods

Target Course: Senior Design Project

- *Problem* narrative: Dynamic mast loading leads to inefficiency or catastrophic failure. A weatherproof, continuous monitor for a mast should indicate flexure along and across the beam. An optical alignment system inside the mast is desired.

- *Data and specifications:* Mast bending characteristics, optical alignment sources, and linear and areal detectors would be described. Typical shipboard mechanical and cabling conditions and power constraints are provided. Temperature and mechanical shock conditions are specified.

- *Soft customer specifications:* All-weather display, visible from the cockpit, and low maintenance are highly desired. Installation should not compromise mast integrity.

- *Customer and instructor materials:* Background on optical alignment principles, line forming optics and competing detector technologies would be included. Budget of about $250 would suffice to make proof of concept system, including rudimentary display. Early thought must be given to testing and calibration of sensor in small mast or similar hollow loaded beam. Access to electronics and small optical bench is needed during calibration of alignment system.