An original syllabus in photonics at the Ecole Généraliste d’Ingénieurs de Marseille

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Abstract: With the creation of a new school of engineers which is part of the French system of the "Grandes Ecoles” a deep reflection based on the experience of three schools, which are merging, has been led. The objective is to prepare highly selected students to meet the need for highly qualified scientists who can become highly qualified managers. The program of education is made of general courses in mathematics and sciences with deepening fields chosen by the students. Optics and photonics are very important parts of the proposed syllabus.

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The French " Grandes Ecoles " are composed of small size institutions delivering degrees after the longest curriculum before a doctorate. These institutions are called " Ecoles d’ingénieurs" in France but it must be noticed that "Ingénieur" comes from the Latin word "genuis" or "ingenium" meaning talent, intellect. In English "Engineer" comes from "engine" that the person having the hands on something to operate it [1].

A little bit more than one percent of a class of age enters the two-year preparatory classes, after a dossier selection process. Students can choose between the different " Grandes Ecoles " depending on the results they obtained in competitive entrance exams. The selection process is based on working capacity (preparatory classes are quite demanding) and the mastering of abstraction measured through an extensive use of mathematics. The recruitment is also opened to high potential foreign students. The selective process is necessary to have students capable in succeeding a dense education for three years.

1. Creation of the "Ecole Généraliste d’Ingénieurs de Marseille"
Photons is a strongly multidisciplinary field. Highly skilled people in this field have a wide knowledge in physics associated with specific competences in optics. In Marseille, after the experience of forty years of teaching to "ingénieurs”, the Ecole Nationale Supérieure de Physique de Marseille decided to merge with two other schools of "ingénieurs” to strengthen the delivered education and to meet the need of companies for managers. The new school, called "Ecole Généraliste d’Ingénieurs de Marseille” (EGIM), delivers a high level of education for engineers and researchers capable in conceiving and managing complex systems, in particular optics based systems, in driving cross-disciplinary teams, in anticipating a quickly changing environment. The opportunity of the creation of this new, fully autonomous establishment belonging to the ministry of education and research, allows defining innovative pedagogical processes. In particular, beyond the conventional lectures, laboratories works, there is also the constant worry of relating one field to another, of keeping the student active, of keeping students’ mind opened and curious, especially to cross-disciplinary approach, of caring about applications. The degree of the "Ecole Généraliste d’Ingénieurs de Marseille” is awarded to successful students after two years in preparatory classes, a competitive entrance exam and three more years including a final year where the students choose a field of interest. This field does not appear on the degree, which is not specialized even though the engineers can be considered as experts in the field. The students are normally 23 or 24 when graduated. They obtained the title of "Ingénieur de l’Ecole Généraliste d’Ingénieurs de Marseille" accredited by the "Commission du Titre d’Ingénieur».

2. Optics and Photonics are pluridiciplinary fields
Optics and photonics are key technologies for numerous application fields like telecommunications, health, microelectronics, defense and security, astronomy, transportations, … They allows tens of millions people to communicate one with the other over the whole world, to cure people, to study the universe and as well to cool atoms as to make control fusion. It concerns also wide public applications like DVDs, illumination, screens, laser shows, …

Very often photonics are only parts of complex systems. As an example a laser system needs competence in basic physics (Quantum Physics, electromagnetism, plasma physics, solid state physics, geometrical and Fourier optics, interferometry, non linear optics, light interaction with matter, signal processing,) as well as in technologies (material properties, optical interference coatings, mechanics, thermal problems, electronics, computing.).

So, beyond scientific and technical knowledge, theoretical and practical competences, a high level optician must be able to manage complex systems, to learn all his life long, but also must be capable in developing industrial processes.

More generally the worldwide economy and technologies, are quickly changing, the earth endures heavy pollutions, inequalities increases. Human and companies managements must not only rely on short-term economic criteria but
sustainable development must also be considered. Scientists must be aware of their role. It then appears necessary to educate future managers so that, added to their excellence in sciences, they behave with an opened mind, as responsible citizens. So the aim of the Ecole Généraliste d’Ingénieurs de Marseille is both to provide a high level scientific education and a humanist culture.

3. Syllabus at the "Ecole Généraliste d’Ingénieurs de Marseille"
The education of each student is based on a strong scientific basis and a wide general culture, extended by acquisition of competences in a more specific field. We are particularly concerned with the development of the entrepreneurship. In perfect agreement with Arthur Guenther [2], we want the engineers to have "transportable skills, critical thinking skills, interpersonal skills, computer skills, communication skills".

As part of the common core, 104 hours of courses are given at all students, and 8 options of 24 hours are proposed directly in photonics. Other courses are of importance for photonics like mathematics, quantum physics, numerical analysis, computing, solid state physics, … In their last year of study students can choose between ten different fields of interest, two of them being directly in photonics. Teaching in each field corresponds to 500 hours. Students must also perform a team transverse project, in which photonics can be a great part, and a training period of 5 months in a company. In their last year of study they also have the opportunity to perform one of the two master degrees proposed in optics (European Master of Sciences in Optics for the Information Society or master "Optique et Signal"). They can also perform a PhD for three more years in one of the international level laboratories of the institution.

So, a great part of the students can benefit of a high level of knowledge in photonics. Each student also benefits of 572 hours of courses aiming at developing a human dimension of the knowledge and competences. 240 hours of courses on foreign languages and cultures are included.

An assessment of competences is set when the student is accepted and regularly actualized so that the student can himself define his curricula and his professional project. We aim to have student actor of his own education.

The team transverse project is performed during the second year of study on a subject proposed by a company. It aims at developing teamwork abilities. A group of 6 to 8 students work together taking into account the costs, the delays, the human relations and produce a report at the end of the work. A professor accompanies the students. The evaluation is performed with the company.

The training period of 5 months in a company, which is a full part of the syllabus, is considered as a first experience in a professional environment. An oral presentation in front of a jury is considered together with a document for the evaluation. Numerous opportunities to perform a full year in a foreign university or in another French school of "Ingénieurs" are offered to students during their last year of study within the scope of exchange agreements.

4. Research
Most of the people teaching in the school have a PhD and lead a research. So, 9 laboratories are directly linked with the school, covering a wide scope of competences. Research in Mechanics, Acoustics, Chemistry, Mathematics, Computing and of course photonics (Fresnel Institute), is performed in the school, in association with the Centre National de la Recherche Scientifique and the universities of Marseille. Such a wide scope of competences gives the school a very important role in developing cross-disciplinary approaches. Doctoral students play a crucial role in research and they play a particular role in inter-linking teaching and research.

5. Partnerships

Companies
Partnership with companies is of major importance in the development of the "Ecole Généraliste d’Ingénieurs de Marseille". Several companies are represented in the Administrative Council that is presided by someone from the industry. They also are strongly represented in the professional orientation committee advertising the administrative council and the director on future evolutions. The scientific council that acts as a visiting committee for research also includes high-level scientists from industry. Many people from industry take part in the education. The team transverse projects are performed in collaboration with companies and the end of study training period takes place in companies. The school is also very active in different thematic clusters of the region like the Optics and Photonics cluster (Pôle Optique et Photonique sud, POPsud), linking more than 70 companies, laboratories and institutions. The school houses POPsud.

Lifelong training developed by the school is also very important in collaboration with companies.

Regional, national and international institutions
The school obtains his main financial support directly from the Ministry of Education and Research, in particular through a four-year agreement. The school has also collaboration agreements with the three universities of Marseille and benefits of financial supports from the regional council of the Provence-Alpes-côtes d’Azur region, the Bouches-du-Rhônes department council and the town of Marseille. A strong collaboration with the commercial and industrial chamber of Marseille is under development.

Exchange students programs are working with nearly 20 high level universities worldwide. The European Credit Transfer System is operational and permits European students to attend some specific courses delivered in the school.

6. Students activities and associations
The student life is encouraged within associations. The student association, the sport association and the art association, together with different clubs (cinema, climbing, diving, music, oenology, astronomy) aim at developing social life and initiatives. The students organize different thematic week, weekends and days all the yearlong.

7. Conclusion
The challenge of engineering education is to simultaneously prepare students for their first job and their career at least 25 years later. This of course applies to photonics. Photonics is and becomes more and more a trans-disciplinary field and this is also a challenge of education. To face these challenges three "écoles d’ingénieurs" decided to merge and to create the "Ecole Généraliste d’Ingénieurs de Marseille". This new institution has defined new curricula based on an innovative pedagogy. Multi-disciplinary basic knowledge is delivered and team project, training period and a strong human education are fully part of the syllabus. The students’ highly selective process is applied to students entering the school so that they can face three years of extensive studies. The core education is delivered during 2 years and a more specific education that can be in photonics is delivered in the last year of study. High-level engineering education must be delivered in an environment of research and industry. Research, relations with companies, participation to the development of local economy, internationality, participation to networks are all necessary to a higher education institution. The "Ecole Généraliste d’Ingénieurs de Marseille" has defined its structure and its objectives in such a way. It aims at developing entrepreneurship, transportable skills, critical thinking skills, interpersonal skills, computer skills, leadership and communication skills.

8. References
From Optics to Optical Engineering: 20 Years of Optics Education at Rose-Hulman Institute of Technology

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Abstract: The optics educational programs at Rose-Hulman Institute of Technology have progressed and evolved over the past twenty years. Beginning with a modest undergraduate area minor in applied optics we now offer bachelors and masters degree programs in optical engineering. Distinctive elements of the current optical engineering programs including courses and curricula will be discussed.

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OCIS codes: (000.2060) Education, (350.4600) Optical engineering

1. Introduction

Rose-Hulman Institute of Technology is a small, primarily undergraduate science and engineering institution although we have an active masters level graduate program in many areas. The institution has been ranked number one in the category of undergraduate engineering schools without a Ph.D. program by U.S. News & World Report magazine for the past four years from 2000 to 2003[1]. RHIT has an outstanding student body. The median SAT scores for the first-year class are 1300. The Department of Physics and Optical Engineering offers B.S. degrees in Optical Engineering and in Physics and an M.S. degree in Optical Engineering. Other areas of study leading to bachelor degrees are: Applied Biology, Biomedical Engineering, Chemistry, Chemical Engineering, Civil Engineering, Computer Science, Electrical Engineering, Mechanical Engineering, Mathematics, Optical Engineering and Physics.

2. History and Evolution of Rose-Hulman’s Applied Optics Educational Programs

Optics educational programs at Rose-Hulman began around 1980[2]. Although an introductory optics had been taught before there was a growing interest by students and faculty to broaden the set of courses offered and introduce modern topics in optics such as lasers and fiber optics. Advice from industrial representatives and other optics educators was critical in establishing criteria for course and curriculum development. These criteria are still used today. First and foremost is an emphasis on hands-on experience for the students through the lab-intensive nature of a majority of the optics courses[3]. Second, we wanted to enhance the student’s technical communication by having them write lab reports, produce project reports and give presentations that were evaluated on the written communication skills as well as the technical content. Other criteria include: integration of computer skills, data acquisition, modeling and simulation.

In the fall of 1983 we initiated what is called at Rose-Hulman an Area Minor in Applied Optics program. An area minor is simply a set of five courses indicating a concentration of elective courses in a specific area of study. The first required courses were: geometrical optics, physical optics, laser physics, optical instrumentation and fiber optics. [4] This program met with enthusiastic response by the students. In fact, the first time that we offered the physical optics course over sixty students enrolled in the course.

The title of Applied Optics was chosen at that time to describe the program content because of the combination of basic optical science courses with courses that included material on optical science and applications of optics. As an example, the laser physics and applications course provided students with a physical foundation in laser science but also covered a number of topics such as laser cutting, laser welding, and applications to biomedicine.

The next step in the development of the applied optics educational programs at Rose-Hulman was undertaken in 1985 when we began offering a masters degree in applied optics. In the masters program the intention was to provide a degree for those students who require additional knowledge of optics beyond the undergraduate level for students entering from a physics background or an engineering background. The program was designed from its inception to be a terminal degree program that prepares students for working in the industry consistent with Rose-
Hulman’s educational philosophy and vision. The students in the program are required to do an optics-related thesis project, and whenever possible, the thesis topic would be a project of interest to an industrial sponsor. By offering a masters degree we complement the undergraduate program with more advanced courses and topics and provide professional development activities for faculty members. To date 69 masters degrees in applied optics have been awarded by Rose-Hulman averaging about four students per year.

Further development of the applied optics program, courses and lab experiments accelerated when the Department of Physics received a grant from Lilly Endowment, Inc. to develop the courses and curricula for the M. S. (Applied Optics) program. One of the unique elements of this grant allowed us to begin a visiting Lilly Fellows program. The visiting Lilly Fellows were leaders in the optics community with educational and industrial backgrounds and included, Brian J. Thompson, Robert E. Fischer, James C. Wyant, and Jean M. Bennett. The visiting Lilly Fellows visited our campus, met with faculty and students and provided input on how we could improve and strengthen our courses and programs.

Encouraged by student interest and feedback from industrial representatives a B. S. (Applied Optics) degree program began at Rose-Hulman in 1988. This program was built upon the experiences and development of the undergraduate Applied Optics Area Minor and the M. S. (Applied Optics) programs. We used the same criteria in developing the courses and curricula for the B. S. (Applied Optics) program as we used previously. Optics courses include laser physics, electro-optics, fiber optics, optical metrology, physical optics, paraxial optics, lens design and aberrations, wave optics and coherence, optical instrumentation, semiconductor devices and materials, applied optics projects laboratory. To date 86 bachelors applied optics degrees have been awarded.

3. Transition to an Optical Engineering

Rose-Hulman has a history of meeting the need for optical engineers via the Applied Optics Programs described above. In fact, many of our program graduates at both the bachelor and masters level have been employed with job titles such as optical engineer and optical design engineer. Feedback from potential employers and former students indicated that the title of applied optics does not carry the same connotations in industry as optical engineering. Some of our students indicated that they believed the title applied optics hindered their obtaining employment with companies that were not aware of our program. Last year, the departmental advisory board that consists of top professionals from the optical industry and education strongly endorsed the name change to optical engineering. Offering B.S (Optical Engineering) and M.S. (Optical Engineering) degrees will hopefully reinforce the idea that we are educating our students in applications of optics that deal with real world problems and practice the profession optical engineering.

An undergraduate optical engineering curriculum is by nature multidisciplinary and must involve a mix of engineering, physics, engineering science and optics fundamentals. In the transition to an optical engineering degree program we are also faced with the task of designing a curriculum to meet not only the growing needs of the industrial market but also to provide our students with a foundation in optical science and engineering.

The current B.S (Optical Engineering) program was built upon the lessons learned in the development of the undergraduate applied optics area minor and bachelors degree programs. Throughout the curriculum laboratory experiments have been developed that reinforce concepts for students to understand basic scientific ideas of a particular subject and gain necessary experimental skills. In addition, we have introduced a sequence of two project-based courses [4] that are intended to awaken the scientific curiosity as well as the engineering creativity of our students.

A list of the optics-related courses in the current B.S. (Optical Engineering) program is given in Table 1. During the freshman year we introduce students to optics topics through a course devoted to holography and photography. Each student makes their own hologram during a workshop session associated with the course. A survey course entitled Optics in Technology provides students with the idea that optics plays a pervasive and enabling role in many familiar consumer products and devices. The curriculum in the sophomore year provides a foundation in optical science and engineering with courses in physical optics, paraxial optics, optical systems and electrical and mechanical systems. During the junior and senior year students take courses that provide depth and breadth in optics that include lasers, electro-optics, fiber optics, optical metrology, lens design and aberrations, semiconductor
devices and materials. Students also take a two course sequence called Optical Engineering Project Lab[4]. In this course the students use their optics background to design, test, and construct a prototype optical part, component, or a system. From an educational perspective this course requires the students to use their optics fundamentals and apply them to a practical problem.

Table 1. UNDERGRADUATE OPTICS-RELATED COURSES AT ROSE-HULMAN

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
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<tbody>
<tr>
<td>OE 171</td>
<td>Holography &amp; Photography</td>
</tr>
<tr>
<td>OE 172</td>
<td>Optics in Technology</td>
</tr>
<tr>
<td>OE 280</td>
<td>Paraxial Optics</td>
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<tr>
<td>PH 292</td>
<td>Physical Optics</td>
</tr>
<tr>
<td>OE 295</td>
<td>Optical Systems</td>
</tr>
<tr>
<td>PH 405</td>
<td>Semiconductor Materials and Devices I</td>
</tr>
<tr>
<td>PH 406</td>
<td>Semiconductor Materials and Devices II</td>
</tr>
<tr>
<td>OE 415</td>
<td>Optical Engineering Design I</td>
</tr>
<tr>
<td>OE 416</td>
<td>Optical Engineering Design II</td>
</tr>
<tr>
<td>OE 450</td>
<td>Laser Systems and Applications</td>
</tr>
<tr>
<td>OE 480</td>
<td>Lens Design and Aberrations</td>
</tr>
<tr>
<td>OE 485</td>
<td>Electro-Optics and Applications</td>
</tr>
<tr>
<td>OE 493</td>
<td>Fiber Optics and Applications</td>
</tr>
<tr>
<td>OE 495</td>
<td>Optical Metrology</td>
</tr>
</tbody>
</table>

Like the B.S. (Optical Engineering) program, Rose-Hulman has also made a transition to offer the M.S. (Optical Engineering) degree. In addition to the thesis project, a total of 36 credit hours of coursework is required. Currently the core course requirements include topics in principles of optics, lens design and aberrations, optical metrology, electro-optics, guided wave optics and Fourier optics. Special topics courses are also offered regularly. Elective courses such as Advanced Image Processing and Biomedical Optics are available to the students.

4. Industrial Outreach Programs

4.1 Center for Applied Optics Studies

At about the same time that the masters degree program was established Rose-Hulman created the Center for Applied Optics Studies (CAOS) through financial support of Indiana’s Corporation for Science and Technology, later renamed the Indiana Business Modernization and Technology Corporation. CAOS has four major functions: 1) Education, 2) Research & Development, 3) Technology transfer, and 4) Service to the industry. Thus, in addition to coordinating the applied optics educational programs, CAOS became an industrial outreach for the institute and a resource to businesses needing optics assistance and expertise.

Over one hundred projects have been completed and titles of many of the technical reports accessed can be online (http://www.rose-hulman.edu/PHAO/). Some of the topics involved in industrial related projects include: fiber optic connectors, fiber optic sensors, image processing, machine vision, photorefractive applications, nonlinear optics, speckle pattern interferometry. Examples of a few of the projects completed by faculty members, undergraduate students and graduate students are: vibration analysis using fiber optic electronic speckle pattern interferometer[5], fiber optic core and cladding diameter measurement [6], investigations of the aging of biological specimen using laser speckles [7], and investigations of photorefractive material properties [8].

4.2 Rose-Hulman Ventures

In 2000 Rose-Hulman started Rose-Hulman Ventures which is a technology-based business incubator collocated with a new product development laboratory. Rose-Hulman Ventures is unique because it is engineering oriented vs. tech transfer oriented, provides on-site product development staff and has direct access to venture capital through its own resources. The facility provides excellent educational opportunities for nearly students and faculty members through their direct participation in the development of the new technology-based products and services of client companies. Optical technology is one of the key supporting and enabling technologies available to client companies. A fellowship for an entrepreneurial M.S (Optical Engineering) student has just been funded that will allow them to pursue their new business and use their ideas for a new optics-related product or service as part of their masters degree thesis topic.
5. Summary

New applications of optics appear everyday. It is imperative that optical science and engineering education continues to evolve to keep pace with these advances. It is also important to provide a balance between scientific fundamentals and discussions about the applications of optics. Laboratory experiments and activities are necessary to optics education and get the students involved and excited about studying optics.

One of the major challenges for the optics community is to increase the source of promising students entering optics at the undergraduate level. Everyone in our field must become involved in encouraging prospective students to study optics and to see that optical science and engineering is an exciting and rewarding career.

6. References

Optics at the Dawn of the Renaissance

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Abstract: Recently, one of us (DH) observed that certain drawings and paintings from as early as the Renaissance seemed almost "photographic in detail. An extensive visual investigation of western art of the past 1000 years resulted in the revolutionary claim that artists even of the prominence of van Eyck and Bellini must have used optical aids. However, art historians insisted there was no supporting evidence for such a remarkable assertion. This paper presents some of the optical evidence we subsequently discovered that convincingly demonstrates optical instruments were in use—by artists, not scientists—nearly 200 years earlier than widely thought possible, and that accounts for the remarkable transformation in the reality of portraits that occurred early in the 15th century.

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OCIS codes: (000.2850) History and philosophy; (000.2060) Education; (100.2960) Image analysis; (100.5010) Pattern recognition and feature extraction

1. Introduction

This paper describes a novel application of known optical principles to an unusual problem, that of analyzing paintings produced as early as the Renaissance to look for evidence of the use of optical devices. The results of our work show that certain artists as early as c1425 used optical projections as aids for producing some elements of their paintings. The discoveries discussed in this paper demonstrate that optical instruments were in use by artists nearly 200 years earlier than commonly thought possible, and account for the remarkable transformation in the reality of portraits that occurred early in the 15th century.

As described elsewhere [1], at a recent exhibition one of us (DH) observed certain qualities in the portraits of Jean-Auguste-Dominique Ingres that suggested to him the artist had used some sort of optical instrument as an aid. This observation of a "photographic quality" in the Ingres portraits developed into an extensive visual investigation of a large number of European paintings of the past 1000 years to determine whether this quality appeared in the work of earlier artists. Briefly, we have now traced this photographic quality as far back as the early fifteenth century. The results of this visual investigation are presented in detail elsewhere along with a discussion of its significance for an understanding of the art of the past 600 years [2].

During the course of this study we became interested in the possibility that optical artifacts might exist within the images of some paintings that could serve as supporting scientific evidence for these visual observations. Certain optical artifacts had been previously identified in some of Vermeer's work in the seventeenth century [3][4][5]. However, it clearly would be of major significance if evidence could be found for use of any optical instrument that pre-dated Girolamo Cardano's 1550 description of a camera obscura that incorporated a lens [6]. In the present manuscript we discuss some of the scientific evidence in three paintings that demonstrate lenses were in use by certain artists to project images as early as c1425.

We presented our initial scientific results in a previous paper [7]. In that paper we concentrated on a remarkable painting by Lorenzo Lotto from circa 1533–4 that actually contains enough information within it to allow us to calculate such details as the approximate focal length and diameter of the lens Lotto used. Having now established visually [2] as well as scientifically [7] that lenses were used by certain Renaissance artists, this discovery has a number of implications for both the history of science as well as the history of art. In this paper we present additional results from our analysis of three paintings. While we include brief discussions of the physical principles behind several optical artifacts, the reader interested in additional details of the underlying optical principles is referred elsewhere [8].

2. The Imaging Properties of Concave Mirrors and Refractive Lenses

In the course of our work we discovered that few non-scientists are aware that concave mirrors can be used to project
images. This is particularly important for several reasons. First, historians unaware of this optical property might erroneously assume that even when a "mirror" is listed in an inventory of an artist's possessions, the absence of a "lens" from the inventory means the artist could not have projected an image. Second, the image projected by a concave mirror gives it one important advantage over that projected by a refractive lens for an artist creating a painting. Since we have discovered a variety of circumstantial evidence that points to the use of such concave mirrors by at least some artists, we explicitly note here that a concave spherical (or parabolic) mirror can function as a "mirror lens." While both refractive lenses and concave mirrors can be used to project images, those from the latter have the advantage that, because a mirror reverses right and left, the symmetry of the image projected by a concave mirror is identical to that of the original subject. The advantages of this for an artist creating an image are discussed elsewhere [2].

Typically, we have found that paintings containing evidence of one optical artifact often contain evidence of others as well. However, length limitations of the present paper make it impossible to analyze a number of paintings in detail, so we have limited ourselves to three early examples here. However, these examples alone provide convincing scientific evidence that lenses were used by artists as early as c1425.

3. Application of Geometrical Optics to Analyze Renaissance Paintings

a. Lorenzo Lotto's Husband and Wife, c1523–4

Analysis of this painting shows how an understanding of geometrical optics and perspective provides a powerful way to show certain images were created with the aid of lenses, as well as to extract quantitative information from those images. Figure 1 is a detail from Lorenzo Lotto's Husband and Wife of c1523–4, showing an octagonal pattern on a table covering that appears to go out of focus at some depth into the painting. Overlaid on the painting are three segments of a perspective-corrected octagon whose details we calculate below. Although there are several features of interest in Lotto's Husband and Wife, here we are concerned only with the way the image in this portion of the painting seems to go out of focus as it recedes into the distance.

While a simple lens can be focused at only one specific distance at a time, the brain causes the muscles of a human eye to quickly and automatically alter the shape to refocus to different depths as the eye traverses a scene. Because of this, we do not simultaneously see part of a scene in focus and part out of focus. In contrast with the eye, no matter what the distance of focus of a simple lens, only a certain field on either side of that distance will remain acceptably sharp, resulting in a depth of field that depends on the focal length and diameter of the lens. To change that distance of focus requires physically altering the position of the lens with respect to the subject and the image plane. Refocusing a lens to a depth further into a scene from its original plane of focus requires moving the lens closer to the image plane (and vice versa). Moving the lens closer to the image plane results in a small decrease in the magnification of the projected scene, as well as in a slight change in the vanishing point, since the lens is now at a slightly different position. While both of these effects are quite small for magnifications M<<1, which is the magnification range for most ordinary photographs, they increase in magnitude as M increases (note that the image of a 1.6 m woman will be ~2 cm tall when projected on a piece of film or a CCD sensor, so M=0.012, whereas the woman in the Lotto painting discussed below is at M=0.56, which is nearly 50× greater magnification). Such effects are fundamental characteristics of images projected by lenses, and are extremely unlikely to occur in a painting if an artist had instead laid out patterns following geometrical rules first articulated in the fifteenth century [9].

Although we discussed several aspects of this painting elsewhere [2,7], here we provide additional details of our analysis. As we showed in Ref. 7, the width of the wife's shoulders in the painting provides an internal length scale that lets us determine the magnification to be M=0.56, and from this we determine the depth of field to be 16±1.5 cm. From geometrical optics the focal length (FL) and magnification (M) are given by:

\[
\frac{1}{FL} = \frac{1}{(d_{\text{lens-subject}})} + \frac{1}{(d_{\text{lens-image}})} \quad (1)
\]

and

\[
M = \frac{(d_{\text{lens-image}})}{(d_{\text{lens-subject}})} \quad (2)
\]

As indicated by the colored segments on Figure 1, there are three regions of this octagonal pattern resulting from Lotto refocusing twice as he exceeded the depth of field of his lens. We label these Regions 1, 2, and 3, with Region 1 the closest to the front of the painting (blue, in Fig. 1). Thus, for the first two Regions,
Fig. 1. Detail of *Husband and Wife*. The blue, green, and red overlays are perspective-corrected sections of an octagonal pattern fit to the painting. If this portion of the painting is based on a projected image of an actual table covering, Lorenzo Lotto would have painted the front (blue) section, then moved his lens to refocus further back when the depth of field had been exceeded and continued to paint the center (green) section, then refocused one more time to finish the final (red) portion. As can be seen, the details of the painting are in excellent qualitative agreement with the three-segment, perspective-corrected octagon predicted by the laws of geometrical optics for such a projected image. As described in the text, the details are in excellent quantitative agreement as well.

\[
\frac{1}{FL} = \frac{1}{(d_{\text{lens-subject1}})} + \frac{1}{(d_{\text{lens-image1}})}
\]

(3)

and

\[
\frac{1}{FL} = \frac{1}{(d_{\text{lens-subject2}})} + \frac{1}{(d_{\text{lens-image2}})}
\]

(4)

However, as we showed in Ref. 7, the measured depth of field is 16 cm, so for Region 2

\[
d_{\text{lens-subject2}} = d_{\text{lens-subject1}} + 16 \text{ cm}
\]

(5)

and

\[
\frac{1}{FL} = \frac{1}{(d_{\text{lens-subject1}} + 16 \text{ cm})} + \frac{1}{(d_{\text{lens-image2}})}
\]

(6)

Because Region 2 is further into the scene, and therefore at slightly lower magnification, than is Region 1, its depth of field will be somewhat larger than 16 cm. However, for the purposes of this paper we will omit this complexity. Thus,
Region 3 of the pattern starts at a depth of approximately $2 \times 16 \text{ cm} = 32 \text{ cm}$ into the scene, so

$$d_{\text{len}} - \text{subject3} = d_{\text{len}} - \text{subject1} + 32 \text{ cm} \quad (7)$$

and

$$1/\text{FL} = 1/(d_{\text{len}} - \text{subject1} + 32 \text{ cm}) + 1/(d_{\text{len}} - \text{image}) \quad (8)$$

The fit of the three segments of the perspective-corrected octagon overlaid on Figure 1 allows us to determine the relative magnifications $M$ of the three regions as 0.56, 0.48, and 0.42, respectively, from which we obtain:

$$0.56 = \frac{d_{\text{len}} - \text{image1}}{d_{\text{len}} - \text{subject1}} \quad (9)$$
$$0.48 = \frac{d_{\text{len}} - \text{image2}}{d_{\text{len}} - \text{subject1} + 16 \text{ cm}} \quad (10)$$
$$0.42 = \frac{d_{\text{len}} - \text{image3}}{d_{\text{len}} - \text{subject1} + 32 \text{ cm}} \quad (11)$$

Thus, we have six equations (3, 6, 8, 9, 10 and 11), but only five unknowns: FL, $d_{\text{len}} - \text{subject1}$, and $d_{\text{len}} - \text{image1,2,3}$. Solving these equations uniquely determines:

$$\text{focal length (FL)} = 53.8 \text{ cm}$$
$$d_{\text{len}} - \text{subject1} = 149.8 \text{ cm}$$
$$d_{\text{len}} - \text{image1} = 83.9 \text{ cm}$$

Note that there are no adjustable parameters in our analysis of this image. In going from Region 1 to Region 2 the magnification, as measured from our fit of a perspective-corrected octagon, decreases by 14.5% from the original 0.56 of the painting, in excellent agreement with the 14.3% we calculate from the above equations. Similarly, the measured magnification decreases by a further 12.3% when going to Region 3, again in excellent agreement with the calculated value of 12.5%.

To summarize, using the measured size of the woman in this painting as the only input parameter, geometrical optics dictates that if Lotto used a lens to project the octagonal pattern there must be three regions corresponding to the depths into the scene where he would have been forced to refove, with three different magnifications, and hence three sets of vanishing points. All of these complex features are found in the painting, and all are in excellent quantitative agreement with the predictions of geometrical optics, providing extremely strong evidence indeed that a lens was used. Further, the focal length of the lens as well as the distances from the lens to the table covering as well as to Lotto's canvas are all quite reasonable, allowing significant insights into the actual layout of the artist's studio.

b. Robert Campin's Merode Triptych, c.1425–28

The earliest optical evidence we have found to date is in the center and right panels of Robert Campin's Merode Triptych of c.1425–28, a detail of which is reproduced in Figure 2. This detail exhibits the same complex change in perspective resulting from having refocused a lens as discussed above for Lorenzo Lotto's Husband and Wife. Overlaid on this painting are three segments of an ideal perspective-corrected lattice that fit the painting to an accuracy of better than 1 mm. Not shown is that a single-segment ideal lattice cannot be made to fit. As can be seen, the latticework in the seat back contains unmistakable evidence of two small changes in perspective that occur at depths into the scene where a lens would have had to have been refocused. A similar change in the perspective at roughly the same depth into the scene also is in the latticework of the seat back in the central panel of this triptych. The complex perspective exhibited by the latticework is an inevitable outcome from the depth of field of a lens, but would be very difficult (and extremely unlikely) to reproduce by any geometrical technique.

c. Jan van Eyck's Arnolfini Marriage, 1434

The perspective, texture, and detail of the complex chandelier in this painting are all quite remarkable, leading us to examine it for evidence that it might be based on an optical projection. The elementary rules of perspective (see, for example, Fig. 24 of Reference 9) seemingly dictate that lines drawn through common elements of an optical projection should meet at well defined foci, all of which must be on a single horizon line. However, any real object, such as a
chandelier, inevitably will deviate from absolutely perfect hexagonal symmetry. While this should be obvious, the consequence of even very small variations is that vanishing points will not obey the simplified laws of perspective as taught in most textbooks [10]. This is shown on the bottom of Figure 3, where lines accurately drawn through corresponding features on a photograph of a light fixture show marked deviation from optical perspective as it is described in elementary textbooks. Interestingly, the top of this figure shows that lines carefully drawn through corresponding features on van Eyck’s chandelier (the tops of the six candle holders) show similar deviations. Although this might seem an obvious test to conduct on an image, as can be seen from these examples, drawing lines on the image of this chandelier is too simplistic an approach to reveal anything useful.

Another important point is that any painting of a three-dimensional object has reduced that object to a two-dimensional space, so some spatial information inevitably has been lost. This is unlike the cases discussed earlier of the Lotto and the Campin paintings, where the carpet and seat back both were two-dimensional. Finally, we note that the decorative elements on the top and bottom of each of the six chandelier arms on this painting obviously would have been attached individually (by soldering or riveting) in fabricating such a complex piece from metal. This easily can be seen by examining a detail of the chandelier arms, as shown in Figure 4. Because of this, the placement of these decorative elements will vary from arm-to-arm, thus making them completely unsuitable for any kind of perspective analysis. For all of these reasons, it is important to analyze appropriate aspects of the chandelier in the painting in order to determine whether or not it was based on an optical projection.

We first need to establish the approximate magnification of the chandelier, since the depth of field of a projected
Fig. 3. (top) Chandelier in the *Arnolfini Marriage*. Lines accurately drawn through the tops of the corresponding six candle holders do not meet at foci on a horizon line as seemingly dictated by the simplified laws of perspective. (bottom) Photograph of a light fixture. Lines accurately drawn through the corresponding six bulb holders show deviations that are remarkably similar to those of the chandelier. In this case there is no doubt whatever the image is based on an optical projection, showing that even slight deviations from defect-free, perfect hexagonal symmetry are sufficient to make inapplicable the simplified laws of perspective.

Image depends on this parameter, and in turn establishes whether or not a lens could have captured the entire image without the magnification-change effects of refocusing described above for the Lotto painting. Comparing the measured height of an actual candle flame, 3.9 cm, to the one van Eyck included in the painting, provides a size scale. We note, however, that none of the conclusions from our calculations are sensitive to the precise height of the flame. With this value, the overall width of the chandelier between opposite candle holders is 96.7 cm, and the magnification is 0.16. This magnification is small enough that the depth of field for a lens falling within any reasonable range of focal lengths would be over 1 m, and hence the entire image could have been captured without refocusing. This would have made the task simpler for the artists and, indeed, makes analyzing the image easier than if it had been composed of several segments.

If the overall image of this chandelier is based on an optical projection, it is reasonable to expect that, after correcting for perspective, the positions of the tops of each of the six candle holders should exhibit something very close to perfect hexagonal symmetry. If, on the other hand, van Eyck painted this very complex three-dimensional object only
by observation, large deviations should occur in the positions of these candle holders. The blue dots in Figure 5 are the positions of the tops of each of the candle holders in the painting after correcting for perspective (i.e. to convert it to a plan view as viewed from the beneath the chandelier, with the candle holders nearest to the viewer at the top of this figure). As can be seen, the agreement with the points of a perfect hexagon is remarkable. The hexagon is rotated 6° counterclockwise, which is due to the chandelier being viewed from that angle. The maximum deviation of any of the candle holders from a perfect hexagon is only 7°, which in turn corresponds to the end of this arm being only 6.6 cm away from its "ideal" hexagonal position. The root-mean-square deviation of all six candle holders from perfect hexagonal symmetry is only 4.2°, or 4.1 cm. While there is no reason to expect a real 15th century chandelier to have been made to an accuracy any greater than this in the first place, there is also the possibility some or all of the individual deviations could have resulted from slight bends during transportation, hanging, or cleaning. As Figure 7 shows, the arms of a 21st century light fixture show imperfections comparable to those on van Eyck's chandelier.

While it would have been relatively easy to have accidentally bent the angular positions of such chandelier arms with respect to each other, or to have attached them with slight errors to the central core, it would be much less likely that the lengths of the arms would vary significantly. Hence, if this painting is based on an optical projection, we would expect the radial positions of the candle holders to deviate much less than their angular positions. Shown in yellow on Figure 5 is a circle through the perspective-corrected positions of the candle holders. As can be seen, the radial positions are identical to within a worst case of only 7.4 mm; i.e., only 1.5% of the radius of the chandelier.

Figure 6 shows the shapes of the perspective-corrected arms of the chandelier, each outlined in a different color, and with the three arms to the viewer's right flopped horizontally so all six overlap. Where the painting doesn't show a complete arm because it is partially hidden by the arms in front of it, only the visible portions are outlined. As can be seen, the main arcs of all six arms are identical to within 5% in width and 1.5% in length. The latter figure is completely consistent with the above, independent, analysis of the radial positions of the candle holders. However, as would be expected for such a complex, hand-fabricated object, there are large variations in the positions of the decorative features attached to those arcs, confirming their uselessness for any sort of perspective analysis.

Given that the arcs themselves are nearly identical, the lowest point on the position of each arc provides an independent set of data to analyze in the same way as we did with the candle holders. With one exception, these lowest points, when corrected for perspective, are in excellent agreement with the same 6°-rotated hexagon as the candle holders. That one exception is the arm extending directly to the viewer's right, which is significantly below the position it would have if it had been faithfully traced from an optical projection (it is nearly the full width of the arm lower than the predicted position).
Fig. 5. The blue ovals mark the perspective corrected positions of the tops of the six candle holders in the *Arnolfini Marriage*. In green is a hexagon, rotated by 6°. The rms deviation of the angular positions of the candle holders from this hexagon is only 4.3°, with a maximum deviation of 7°. Assuming a magnification of 0.16 as determined from the measured height of a candle flame, the yellow circle through the candle holders has a diameter of 96.7 cm. The maximum radial deviation of any of the six candle holders from the radius of this circle is only 7.4 mm (1.5%).

To summarize the evidence that van Eyck's painting of this chandelier is based on an optical projection:

1) The perspective-corrected length, width, and shape of the main arc of all six arms are identical to within ~2%;

2) The perspective-corrected radii of all six candle holders are within ±1.5% of the radius of a perfect circle centered on the axis of the chandelier;

3) The perspective-corrected angular positions of all six candle holders are within ±4° of the points of a perfect hexagon;

4) To within ±1 mm on the painting, the positions of the lowest points on the arcs of five of the six arms have the identical perspective-corrected hexagonal symmetry as the candle holders, with both sets of data rotated by the same 6°;

5) The vanishing points defined by the candle holders as well as by the lowest positions of the arcs converge to the same horizon to within the accuracy expected for the imperfections in a real chandelier;

6) Qualitative: the overall size of ~1 m estimated from the height of the candle flame is physically reasonable, as are the minor variations in the lengths and angles for such an ornate, hand-made object. Our analysis of photographs of two six-arm lighting fixtures (one of which is shown in Fig. 3) taken from approximately the same viewpoint as the chandelier finds angular and radial deviations of the perspective-corrected positions of their light bulb holders of relative size comparable to that of van Eyck's chandelier, as well as perspective lines that do not come to well-defined vanishing foci on a single horizon line.
Fig. 6. The outlines of all six arms on the Arnolfini chandelier in different colors, corrected for perspective and with the arms to the viewer's right flopped horizontally to overlay on the arms to the left. As can be seen (highlighted in grey), the main arc of all six arms are the same to within 1.5% in length and 5% in width. However, as would be expected, there are significant variations in the locations where the decorative elements are attached to each of the arms.

From the above evidence, with a high degree of certainty we can conclude that van Eyck's chandelier is based on an optical projection of a real chandelier. Although there are some small differences (e.g. the height of one arm) that provide insights into artistic choices van Eyck made to deviate from tracing the projection, possibly to accentuate some features, overall the remarkably realistic perspective of this complex object is a result of the optical projection technique used as an aid by the artist.

4. Summary and Conclusions

The elements of three paintings we have analyzed in this manuscript contain optical evidence showing that lenses were in use for projecting images nearly 200 years earlier than previously even thought possible, and account for the remarkable transformation of the reality of portraits that occurred early in the 15th century. We emphasize that this evidence shows that some features of some paintings were produced with the aid of lenses. However, useful as it is as a tool, a lens does not arrange a composition, fill in the colors or shadings, or make any of the many other artistic decisions that are needed to create a painting. More information on optical aspects of this topic can be found at:

http://www.optics.arizona.edu/ssd/FAQ.html

5. Acknowledgments

We gratefully acknowledge David Graves, Uلت Guilloyle, Martin Kemp, José Sasián, Richard Schmidt and Lawrence Weschler for a variety of valuable contributions to our efforts.
6. References


6. Hieronymi Cardini (Giorolamo Cardano), De Subtilitate, Book XXI (Nuremberg, 1550).


Abstract: It is well known that computer simulations can aid the understanding of complex devices and systems, particularly if they allow the students to modify parameters and see the results on laboratory-like virtual instrumentation. However, a drawback of commercial simulation tools is that they cannot be distributed freely to students, for ‘take-home’ assignments. To address this problem, VPI has developed VPIplayer™, which has the full simulation capabilities of VPItransmissionMaker™ and VPIcomponentMaker™, including exactly the same numerical models as the full commercial tools. VPIplayer can illustrate basic concepts through to complex systems designs, and is distributed freely to anyone with a PC. This paper discusses the advantages of using commercial software in education, introduces VPIplayer and how to create Virtual Laboratories, charts the range of possible experiments, and provides some illustrations of virtual ‘take home’ laboratories.

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1. Numerical Modelling Software for Teaching

Educational institutions are continually asked to make courses more relevant to current industrial practice, yet also have to provide students with a thorough understanding of fundamental concepts, so that students are ‘future proofed’. As technology progresses, the gap between these requirements widens, or one side becomes ignored completely.

A common compromise is to teach theory (usually analytical solutions) in the lecture theatre, and leave practical aspects to laboratories and design projects. Unfortunately, this often means that lectures are ‘dry’, as real-world solutions often go beyond the mathematical prowess of undergraduates, and often beyond the reach of analytical solutions altogether. The other problem is that real-world laboratories are equipped with millions of dollars of equipment, which universities can never emulate, and also carry safety hazards and high maintenance costs.

Fortunately, numerical models can help bridge the gap between analytical solutions and realistic engineering design. This is because a numerical model is based on fundamental mathematics (such as differential equations), but can extrapolate to extremely complex situations. Thus, students can test that a numerical model agrees with analytical solutions in simple cases, and then extrapolate to complex designs using the model. Ideally, they will gain some understanding of how the algorithm works.

Industry has embraced commercial numerical modelling software, as it supports creativity beyond analytical solutions, and also captures the design details during use [1]. It also supports collaborative design amongst teams and between vendors and customers (‘design chains’) [2]. It is also essential for verifying designs, and optimizing production yields.

There are a number of software packages aimed at education and training, many of them developed in-house. However, using commercial software for teaching gives several benefits for the students:

- Students get to see professionally-written software applications and graphical interfaces
- Students work on realistic design problems (such as applications demos supplied with the software)
- Students learn that there can be many solutions to the same problem (e.g. many ways of transmitting a Tbit/s or generating a modulated optical signal)
- Students can put something relevant on their CVs
Commercial software also has several benefits for the educational institution:

- The software contains hundreds of years of development work
- The software is well-tested
- The software comes with extensive manuals and applications examples
- Updates to the software and demos occur automatically, so is always ‘fresh’
- Students can exchange ideas with industrial users using on-line forums linked to the software.

The main disadvantage, addressed here, is that commercial-grade software cannot be given away for free to the students for use off-campus. This is for the simple reason that the free software will undermine the commercial market, so eventually all development and support of the software will cease because it becomes unprofitable. One option is to provide cut-down simulation tools, with a limited range of models. Unfortunately, this means that the more interesting effects and phenomena cannot be explained.

2. Free Take-Home Virtual Laboratories

To address this problem, VPI has developed VPIplayer™. This has the full simulation capabilities of the commercial tools VPItransmissionMaker™ and VPIcomponentMaker™, including exactly the same numerical models. Thus students get realistic results without compromise. VPIplayer can be downloaded from http://www.vpiphotonics.com/VPIplayer

VPIplayer is shown in Fig. 1. This GUI appears if a dynamicDataSheet™ is opened, say from an email, server or webpage. A dynamicDataSheet is a term coined for the commercial market, where vendors what to promote components and sub-systems to equipment manufacturers. For the purposes of the article a dynamicDataSheet is synonymous with a Virtual Laboratory. The top of the GUI shows the schematic of the system being simulated, including instrumentation. This uses Adobe’s SVG vector graphics format that can be zoomed into without losing detail. This allows annotations and parameter values to be seen, even of very complex schematics.

![VPIplayer GUI](image-url)

Fig. 1: VPIplayer after a dynamicDataSheet for a mode-locked laser has been opened.
The buttons at the bottom-left allow (1) new dynamicDataSheets to be opened, (2) simulations to be run, and (3) emails sent to the originator, or the originator’s web-page to be accessed. This feature is useful when submitting questions to the course coordinator, or looking for updated tasks.

Above these buttons is an attachment area. This can show information relevant to a particular schematic, like course notes, spreadsheets with analytical solutions, mathematical modeling programs, or presentations.

To the right of the buttons is an area for controls. These controls allow certain parameters of the simulation to be changed before each simulation run. In the case of Fig. 1, the delay of the external cavity can be adjusted. This allows students to investigate harmonic mode-locking and unstable pulse generation. These controls can also be lists, such as lists of component choices or preferred values.

Running a simulation produces results presented within sophisticated visualization tools. The tools allow data to be examined and post processed after a simulation. For example the WDM Channel Analyzer (Fig. 2) can:

- Display the spectrum of multiple channels
- Display the waveform of a selected channel
- Display the Poincaré sphere of any channel
- Display the Eye diagram of any channel, including BER contours
- Plot BER versus Received Optical Powers for all channels
- Calculate Signal Powers, Noise Powers, Optical Signal to Noise Ratios, BERs, Q-factors and effective Q-factors for all channels
- Apply dispersion compensation to each or every channel
- Apply attenuation to each channel
- Display timing and amplitude metrics for all channels

Fig. 2: The WDM Channel Analyzer provides a wealth of functionality in one visualizer
Other visualizers include:

- Optical and electrical oscilloscopes with inbuilt filters and resolution controls
- Eye diagrams with BER contours
- Optical spectrum analyzer with phase, dispersion, delay and Stoke’s vector plots
- Histogram with curve fitting
- Tabular display for spread-sheet type data
- Poincaré sphere to view polarization states (and their frequency dependence)
- Displays of fiber internal states, laser performance plots, dispersion and power plots, amplifier metrics, and almost any performance measure in an optical system

A range of applications demos also shows the operation of laboratory equipment and common test and measurement techniques [3], including the imitations of these techniques.

3. Generating dynamicDataSheets (Virtual Laboratories) for distribution

Over 150 universities have purchased the full versions of VPIsystems’ simulation software, VPltransmissionMaker™ and VPlcomponentMaker™. These share a common interface, and allow almost any experiment to be assembled from over 700 generic photonic and electronic modules. Also, there are over 350 ready-made demos, which can be modified if desired.

Schematics created in VPltransmissionMaker/VPlcomponentMaker can be exported as a dynamicDataSheet for free distribution and use with VPlplayer, as shown in Fig.3. This is a simple process:
Define which parameters are to be available as controls (sliders or lists) in VPIplayer. This involves selecting ‘Create Player Parameter’ from a context sensitive menu in the parameter editor for that component. If not already specified, the max and min ranges will have to be specified.

Attach any documents to the schematic that should appear in VPIplayer

Select ‘File → Export → dynamicDataSheet’, then completing the contact details and web-page details. A university logo can also be added at this stage.

The completed dynamicDataSheets are very compact (10-40 kB) so can be distributed electronically using email or web-page downloads. If desired, they can be locked with a password. This could be useful if a start-date is specified for an assignment; the password should be distributed on that start data.

4. Full Versions of the Simulator

VPItransmissionMaker/VPIcomponentMaker share a graphical design environment, so that new components, subsystems, systems and networks can be defined by wiring modules together in a schematic. This design environment is shown in Figure 4. The modules are selected from a library on the left, and placed onto a schematic. Different parameter values can be set for each instance of a module on a schematic, or parameters values may be linked to common ‘global’ parameter settings (say to set the bandwidths of all optical filters at once).

![Graphical Design Environment of VPItransmissionMaker/VPIcomponentMaker showing component libraries (left) and Interactive Controls (lower-right window)](image)

Once the schematic has been created, simulations can be run and visualizers will appear, just as in VPIplayer. However, design process tools are provided to speed the design process, such as:

- Design Assistants to replicate keyboard and mouse actions, so that topologies can be automatically synthesized by answering questions in a wizard
Simulation Scripts to control multiple simulation runs, setting parameters, manipulating data and sending results to files

Interactive Simulation control panel, to drive a design process through annual tuning, multidimensional parameter sweeps, optimization and yield estimation

Remote simulation server controls, so that large jobs can be sent to one or more simulation servers

Third party (and in-house) software can be accessed ‘live’ using cosimulation interfaces.

Table 1 compares the features of VPIplayer and the full simulation tools. One important point is that the simulation engine within VPIplayer is identical to that within the full tools. This means that VPIplayer will generate exactly the same results as the full tool.

<table>
<thead>
<tr>
<th>Feature</th>
<th>VPIplayer</th>
<th>VPItransmissionMaker</th>
<th>VPIComponentMaker</th>
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<tr>
<td>Schematic Editor</td>
<td>View Only</td>
<td>View and Edit</td>
<td></td>
</tr>
<tr>
<td>Schematic Hierarchy</td>
<td>View Top Level Only</td>
<td>View and Edit (any level)</td>
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5. Applications Coverage

VPIplayer dynamicDataSheets can be created from scratch using the almost infinite number of combination of the 700 photonic and electronic modules in VPItransmissionMaker and VPIComponentMaker. However, it is easier to start from the existing demo set, of which there are more than 350. These demos cover the following categories:

**Conceptual**

These examples illustrate the some physical phenomena in isolation and are intended for comparison with analytical formalisms as found in text books:
Coherent and Incoherent light sources
Optical couplers: phase shift
Fabry-Perot resonators: free spectral range and tuning
Interferometers: optical interference in the time domain
MZI modulators illustrating optical chirp
Intensity-modulated optical spectrum
Gaussian pulse broadening in dispersive fiber
Chirped Gaussian pulse broadening in dispersive fiber
Self-Phase Modulation: Soliton propagation in nonlinear fiber
Cross-Phase Modulation: Jitter in WDM systems
Four-Wave Mixing in optical fibers
Coherent and Incoherent optical crosstalk
Direct and coherent optical detection
First-order, second-order and all-order PMD
Raman gain and power transfer in optical fibers
Brillouin scattering in optical fibers

Instrumentation
These examples illustrate the basics of laboratory instrumentation, and are best used with a text on Fiber Optic Test and Measurement [3]:
- Operation of an Optical Spectrum Analyzer
- Amplitude and timing metrics from an oscilloscope
- BER estimation by error counting
- RIN measurement
- Linewidth from the frequency fluctuation spectrum
- Linewidth using heterodyne detection (with a second laser)
- Linewidth using self-heterodyne detection (with a delay line and frequency shifter)
- Linewidth using self-homodyne detection (with a delay line)
- IM and FM response measurement for lasers
- Side-Mode Suppression Ratio Measurement
- Modulator chirp from the modulation response
- Modulator Extinction Ratio (ER) using RF Power Meters
- Chromatic Dispersion by Delay Measurement
- Chromatic Dispersion Modulation Phase Shift Method
- PMD by Fixed Analyzer Method (null counting)
- PMD by the Pulse Delay Method
- PMD by the Modulation Response Method
- PMD by Jones Matrix Eigenanalysis
- PMD monitoring insensitive to chromatic dispersion
- Amplifier gain slope measurement
- Swept homodyne interferometry (for CD/DGD/PMD/PDL)
- Optical Amplifier Characterization

Components
These examples illustrate the behavior of components in isolation.

Light Sources:
- Laser Light-Current characteristics (edge emitting and VCSEL)
- Laser frequency fluctuation spectrum, optical spectrum and linewidth
- Laser intensity noise and RIN spectrum
- Small signal IM and FM modulation response
- Laser transient response (Rate Equations), Laser chirp (transient, adiabatic and SHB)
• Effect of optical feedback- RIN and chaos
• Biasing a laser for fast response, low jitter and reasonable extinction ratio
• Multi-mode lasers: effect of material gain spectrum
• Single mode lasers (DFB, external cavity, and Gain-coupled)
• Vertical-cavity lasers (L-I characteristics and modulation response including thermal effects)
• Mode-locking techniques
• Multi-section and tunable lasers
• Light-emitting diode spectrum and modulation response

Modulators:
• Mach-Zehnder modulators: drive configurations, extinction ration and chirp
• Electro-absorption modulators: static and dynamic characteristics
• Integrated lasers and EAMs: effect of feedback into the laser section

Doped fiber amplifiers:
• Pumping schemes: forward, backward, dual, multi-section
• Pump power conversion efficiency
• Gain and noise figure spectra
• Saturation of gain at high input powers
• Higher-order effects
• Waveguide amplifiers

Raman fiber amplifiers:
• Raman gain spectrum: relation to the gain coefficient and pump wavelength
• Signal, pump and noise powers along a fiber
• Pumping schemes: backwards/forward single/multiple
• Polarization issues: pump multiplexing
• Multi-stage and hybrid amplifiers

Dispersion Compensators:
• Fiber Bragg Grating compensators
• Dispersion-Compensating Fiber
• Multi-Ring Resonators

Receivers:
• Shot noise (Quantum Limit)
• Thermal noise
• Receiver bandwidth and noise filtering
• ASE beat noise (SxN, NxN), optical filtering
• Relationship between BER and Received Optical Power (thermal-noise limited)
• Effect of ASE on BER versus ROP
• Avalanche Photodiodes
• Optically-preamplified receivers: improvement in sensitivity
• Transimpedance Amplifiers
• Limiting Amplifiers
• Clock and Data recovery: resonator circuits
• Clock and Data recovery: phase-locked loops
• Thresholding and Retiming
• Decoding and FEC gain

Optical filters:
• Filter bandwidth and dispersion
• Fabry-Perot Filters
• Mach-Zehnder Filters
• Mach-Zehnder filters with passband flattening
• Fiber-Bragg Grating filters
Arrayed Waveguide Filters

Systems
These examples illustrate how components can be assembled into systems of increasing complexity:
- Single-channel attenuation-limited unamplified system: BER versus length
- Single-channel dispersion-limited system: BER vs. ROP for various dispersions
- Single-channel optically-preamplified system: effect of optical receiver bandwidth
- Single-channel and WDM soliton systems
- Coarse-WDM system, Dense WD system
- Multi-span amplified system (‘58’ equation)
- Dispersion maps: pre-compensation versus post compensation
- RZ versus NRZ systems
- Chirped-RZ systems
- Vestigial side-band modulation
- Dispersion-supported transmission
- Optical single-sideband modulation
- Phase-shift keyed systems
- Raman amplification in systems: upgrade strategies
- Polarization Mode Dispersion: degradation and compensation
- Optical time-division multiplexing (OTDM)
- Passive optical networks
- Broadband access networks using CATV infrastructure
- Analog and sub carrier transmission

Optical Subsystems
These examples illustrate emerging technologies based on photonic signal processing:
- Optical gates (based on Semiconductor optical amplifiers, SOAs)
- Sagnac loop demultiplexers for OTDM signals
- SOA wavelength converters: XPM, XGM, FWM
- Optical clock recovery
- WDM to/from TDM format conversion

Optical Networks
These examples illustrate more complex systems technologies with end-to-end optical paths:
- Networks with OADMs
- Networks with OXCs
- OXCs with wavelength conversion capability
- Optical crosstalk issues
- Protection switching
- Networks incorporating long-hauls links.

6. Ready-made VPIplayer dynamicDataSheets for educational use
A set of VPIplayer dynamicDataSheets have been created especially for the popular undergraduate and graduate textbook by Gerd Keiser “Optical Fiber Communications”, McGraw Hill, Boston, 2000. The downloads are available from http://www.mhhe.com/engcs/electrical/keiser/.

- BER vs. Dispersion: (Chap 3 and 7) This demo shows the effects of chromatic dispersion on signal quality, as displayed on an eye diagram.
- BER vs. Extinction Ratio: (Chap 7) This demo illustrates the BER as a function of the extinction ratio (ER) for a system without optical amplifiers.
• **BER vs. Extinction Ratio (Amplified System):** (Chap 7 and 11) This extension of Demo #2 includes the effects on ER when an optical amplifier is included in the system.

• **BER vs. ROP with Channel Analyzer:** (Chap 7) This provides an efficient method of calculating and plotting BER versus Received Optical Power.

• **Black Box versus Full EDFA model (980nm Pump):** (Chap 11 and 12) This demo compares three different simulation models. Some suggestions for this demo: Compare the noise figure (NF) and gain for different pump powers.

• **Black Box versus Full EDFA model (1480nm Pump):** (Chap 11 and 12) Same comment as for Demo #5.

• **CNR, CSO, CTB, IMD CATV Measurements:** (Chap 9) This demo illustrates various performance parameters of a 20-channel NTSC analog system.

• **Directly Modulated Laser System:** (Chap 3, 4, and 7) This setup shows how the chirped output waveform from a directly modulated laser interacts with fiber dispersion to cause pulse spreading.

• **Dispersion Managed Sections:** (Chap 11 and 12) This setup demonstrates the use of dispersion compensating fiber (DCF) to mitigate the effects of chromatic dispersion in a link. Different fiber span lengths and attenuation values can be selected.

• **EDFA Gain and Noise Figure Characterization:** (Chap 10 and 11) This demo characterizes the gain and noise figure of an EDFA.

• **EDFA Gain versus Input Power:** (See Figure 11.3 in Chap. 11) This illustrates the gain versus optical input power characteristics of an EDFA.

• **EDFA Pre amplifier Design:** (Chap 11) This demo allows many variations on EDFA design configurations, such as 980 or 1480 nm pump wavelengths, forward or backward pumping, and different EDF lengths.

• **Four Wave Mixing:** (Chap 12) This demo illustrates the growth of four-wave mixing effects. The simulation takes some time to run, since it goes through 50 loop cycles. During the simulation the degradation in the eye diagrams with each successive simulation loop can be seen.

• **NRZ Pre/Post Compensation:** (Chap 8 and 12) This module compares the effectiveness of three different dispersion compensation methods for NRZ formatted signals.

• **OSNR vs. Transmission Distance:** (Chap 6, 8, and 11) This demo shows the build-up of ASE noise along an amplified link. In the “XY: Power, Noise, and OSNR vs. Distance” display, the top trace gives the OSNR.

• **Raman Gain Characterization:** (Supplement to Chap 11 and 12) This setup demonstrates how to measure the gain of a distributed Raman amplifier. In the "XY: Power Distribution" display, the top curve is the optical power level in the fiber from the Raman pump laser (using backward pumping). The bottom set of curves are the signal power levels for the different WDM channels.

• **Relative Intensity Noise:** (Chap 9) This setup shows how the relative intensity noise (RIN) can be determined as a function of the frequency, and the effect of laser bias current on RIN and its spectrum.

• **Time-Resolved Frequency Chirp:** (Chap 8) This module shows how to characterize the dynamic chirp of a laser.

### 7. Conclusions

VPlplayer provides free take-home laboratories and is based on the full capabilities of professional photonic simulation tools. This combination gives students the 'industrial' simulation power at no cost. The downside, if it can be called that, is that the experiments have fixed topologies, and a few variable parameters. However, this may actually be an advantage, as it focuses students on a prescribed parameter space. For postgraduate students, who wish to create new topologies and component libraries, VPIphotonics offers discounted versions of its full professional tools VPIcomponentMaker and VPItransmissionMaker.

### 8. References

Growing a photonics program in good times and bad

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jdonnelly@trcc.comnet.edu

Abstract: Three Rivers Community College began an associate degree program in Photonics Engineering Technology in 1998 when telecommunications was booming. Five years later the program continues to grow. Support from industry and from the National Science Foundation have been key to keeping the program moving forward. Creating a pipeline of entering students remains a challenge.

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1. Introduction

Three Rivers Community College (TRCC) is a public, associate degree-granting college located in southeastern Connecticut. Formed in 1992 by the merger of Thames Valley State Technical College and Mohegan Community College, TRCC is a comprehensive multi-campus college with a full range of programs in technology and engineering technology. Although Connecticut is located in what has been called "Photonics Valley", stretching from Virginia to Massachusetts, eastern Connecticut has few optics related companies and is mainly known for two large Indian gaming casinos and the submarines built at General Dynamics Electric Boat Division in Groton. Yet TRCC has created a two-year associate degree program in Photonics Engineering Technology which continues to grow. This paper describes the development of a photonics technician program at a distance (in Connecticut terms) from supporting industries and explains strategies used to keep the program current with industry and student expectations.

2. The first few years

2.1 Initial program development and approval

The Three Rivers' Photonics Engineering Technology (PET) program resulted from one of the authors (JD) growing restlessness after many years of teaching mainly Newtonian physics to technology students. A course in optics and modern physics had been discontinued in the late 1980s and, around the same time, a conversion from a quarter to a semester calendar reduced the number of students taking second semester physics, which included waves, sound and light. An offer to participate in a National Science Foundation Advanced Technology Education (NSF-ATE) supported professional development project in fiber optics technology was thus greeted with enthusiasm.

The Fiber Optics Technology Education Project (FOTEP) was administered by the New England Board of Higher Education (NEBHE), and the Fall 1995 FOTEP workshop was the beginning of a long and fruitful relationship between TRCC and NEBHE. Held at Springfield (MA) Technical Community College, the workshop introduced participants to fiber optics technology and its seemingly boundless career opportunities. Each participating school was given a set of tools and a test set for fiber connectorization (half paid for by the grant and half by the participating institution) and each participating teacher practiced using the equipment to terminate multimode cables with ST connectors. The participants were then instructed to incorporate the new knowledge into their own courses. Additional workshops held in the summers of 1996 and 1997 provided participants with more detailed information on fiber optic communications systems and gave them the opportunity to network with each other and with FOTEP's industry advisors.

At TRCC, the FOTEP workshop led initially to the creation of a four credit laboratory course, Introduction to Photonics, which was offered as a technical elective course to interested students. The publication of the first National Photonics Skills Standards [1], and the prediction that the number of photonics technician jobs would double in the coming few year prompted TRCC Dean of Technical Education Thomas Kidd to convene a Photonics Steering Committee in March 1996. The five companies represented at the initial meeting were engaged in the design, manufacture, or installation of fiber optic systems and components, and each enthusiastically endorsed the idea of a two year degree to train photonics technicians. Notes from the first steering committee meeting indicate that industry representatives declined to review the detailed skills standards, but preferred to create a short list of characteristics desired in a new employee. Committee members were anxious that students be proficient in geometry
and trigonometry, have well developed English communications skills, be good "team players", and have positive "work ethics" training. Basic optics and electronics lab skills were desirable, but each company suggested that they would prefer to train employees on their own systems and to their own standards.

The actual curriculum development proceeded along practical lines: the program was to cost as little as possible to develop and administer, while meeting the guidelines of both the Community Technical Colleges and the Department of Higher Education. The former had a strict 68 credit limit for associate degree programs, and the latter an interest in balanced programs with a large percentage of general education credits. The PET program was created through compromise: existing courses from Electrical Engineering Technology were supplemented by courses in laser safety, optics, lasers and fiber optics. The optics/photonics courses, each of which has a laboratory component, were designed with assistance from the Laser Electro Optics Technology program at Springfield Technical Community College. Following the requirements of the Electrical Engineering Technology program, the math sequence proceeded from PreCalculus through Calculus II, and the program included seven electrical/electronics courses. Initially, little was done to integrate the existing electronics courses with the new photonics courses.

The program was enthusiastically approved by the Community College Board of Trustees in December, 1996. The approval of the Department of Higher Education followed six months later. The June approval precluded recruiting a class for Fall 1997, nonetheless, the first optics course was offered in September 1997 to approximately 10 students, four of them declared PET majors or Electrical Engineering Technology double majors.

2.2 The first laboratory
For the first two years, laboratory experiments were performed in a variety of locations, including the physics and electricity/electronics labs. FOTEP had provided hand tools and an LED test source and meter for applying connectors to fiber optic cable, and the physics lab had a variety of light sources, including HeNe lasers and inexpensive optical components and mounts. The first priority was to obtain basic equipment for optics and fiber optics.

In 1997, Three Rivers became a partner in the newly created Northeast Center for Telecommunications Technologies (NCTT, now the National Center for Telecommunications Technologies), an NSF-ATE Center located at Springfield Technical Community College and created in partnership with NEBHE. NCTT provided professional development workshops, as well as funding for partner schools to assist in starting new courses and programs. At Three Rivers, NCTT grant funds were used to purchase additional tools and test equipment for fiber optics as well as a small optical breadboard, components and hardware. Funding was also used to create marketing brochures and to hire student technicians to assist with setting up and testing newly developed laboratory experiments.

By the fall of 1998, it was evident that more appropriate space was needed. Room darkening shades had been added to the physics laboratory, but if was impossible to completely block sunlight from entering the large south facing windows. A small darkroom, once the technical college's yearbook photography lab, became the first dedicated optics lab. After extensive cleaning, the walls were painted flat black and a green safelight was installed for use with red sensitive holography film.

3. Growing in industry boom times
3.1 Marketing
The years from 1998 to 2001 saw rapid growth in the program as measured by enrollment and acquisition of laboratory equipment. Enrollment surged from 4 students in the spring of 1998 to 35 in the fall of 2001. Several marketing initiatives contributed to this growth.

- High school mailings: Since photonics was a new and unknown word, marketing materials were developed, including a poster and brochure. These were distributed to teachers and guidance/career counselors at the 20 high schools in the college's Tech Prep consortium. Teachers were invited to bring students to visit the College for demonstrations and lab tours.
- Appeal to graduates: A list of recent graduates in the Electrical Engineering Technology program was obtained, and a special informational mailing invited graduates to earn a second degree with "only four more courses". Similar information was made available at the U.S. Naval Submarine Base, also located in southeastern Connecticut.
- Industry awareness: Using various resources including the Internet and telephone and industry directories, a mailing list of Connecticut photonics related industries was created. A newsletter was produced to bring
awareness of the new degree program to companies that might provide support through donations of materials or hiring program graduates. A newsletter is still sent out to the industry mailing list and to high schools in eastern Connecticut approximately twice a year. The newsletter includes information about program activities, curriculum changes, and student awards and achievement, and it publicly acknowledges companies that have provided assistance such as hosting tours or making donations.

- JDS Uniphase Scholarship: From 1999-2001, JDS Uniphase/Electro Optics Products Group (Bloomfield, CT) offered one new scholarship each semester to a Photonics Engineering Technology student. The award covered all costs of the degree, including tuition, fees, books and required supplies, a total of approximately $3500 per year per student. Not only did the scholarship bring excellent new students to the program, it also created a superb marketing opportunity, since newspapers and high school guidance offices actively promote scholarship opportunities.

The program continued to expand in other ways. In response to an invitation received by mail in Fall 1998, PET students requested permission to form a chapter of SPIE, the International Optical Engineering Society. By Spring 1999 a constitution and bylaws had been written and the group sought and received operational funds from the college's Student Government. This funding supported field trips to companies throughout Connecticut and Massachusetts and provided gifts for industry speakers who addressed the group on campus.

The SPIE student chapter rapidly became the outreach arm of the program. Not only does it continue to fund yearly trips to industry and trade shows such as Photonics East and the New England Fiber Optics Council's Fiberfest, but it is also a visible group on campus, raising awareness of the program and photonics technology. In 2001, the chapter received a grant from SPIE which was used to create an "educational light show" with a script describing optics technology and careers and special effects and music to appeal to a high school audience. The show is a regular stop for visiting high school groups, and students have taken it to other venues as well, including two appearances at a regional conference of the Technology Student Association. The chapter has also conducted fundraisers for a chapter volunteer excellence award, and in 2003, they invited the college community to join them in an event to celebrate Worldwide Pinhole Camera day. Each event provides the opportunity to leaflet both campuses with signs bringing attention to both the SPIE student chapter and the PET program.

In addition to day and evening credit courses, non-credit hands-on fiber optics workshops were developed through the college's Continuing Education department. Introductory and Advanced workshops continue to be taught yearly, attracting students from business, industry and the military. Teachers in area high schools have also been invited to attend at no cost, with expenses paid by the college's Tech Prep program.

2.1 Laboratory improvement

In 1998 the program received a $51,000 grant from the National Science Foundation Instrumentation and Laboratory Improvement program (NSF-ILI) for the development of a laboratory for lightwave communications.

The grant allowed the creation of three lab stations: two stations for fiber splicing and test and a station for demonstrating wavelength division multiplexing at 1310 nm and 1550 nm. Along with the fiber termination equipment previously obtained from the FOTEP project and NCTT, two fusion splicers and two optical time domain reflectometers (OTDRs) were purchased to allow students to create and test long fiber links. Two fiber coupled lasers and WDM couplers were purchased, and JDS Uniphase donated lithium niobate modulators. Table 1 lists the equipment specified for the Lightwave Communication Laboratory. Note that the cables were donated by NCTT and Chromatic Technologies, allowing additional equipment to be purchased with grant funds. Chromatic Technologies also donated two additional older model OTDRs. Older models of equipment are usually of a simpler design and allow a more straightforward introduction to an instrument before the more complex menu driven instrument is used.

Although the college was obliged to match only the dollar amount of the equipment grant, a large college overmatch plus a round of industry donations brought an assortment of lasers, components, mounts, optical rails, and breadboards to the program. A 5'x8' optical table was purchased for the small darkroom (now known as the Holography/Interferometry Lab). While most donations were accepted enthusiastically, one particularly large "gift" emphasized the need for caution when accepting industry donations. The college had been informed of a large quantity of fiber and "associated components" being surplussed by a large company. The fiber optics course and the Continuing Education fiber optics workshops have a constant need for optical fiber, so students consume fiber and cables while practicing splicing and connector application. After examining the list of available items, the college expressed a desire to accept the some of optical fiber. The actual donation consisted of several dozen large, sealed boxes, some containing hundreds ferules and obsolete fiber connectors, hundreds of specialty electronic
connectors, boxes of colored coating pellets and bags of unidentifiable parts. There were indeed several hundred spools of fiber included, but since all identifying marks had been removed they were of value only for an exercise in identification of unknown fiber. As a result of this experience, donations, while still gratefully received, are thoroughly investigated before acceptance.

Table 1 Lightwave Communication Laboratory

<table>
<thead>
<tr>
<th>Station 1 and 2: Fiber splicing and test</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Siecor compact fusion splicer kit</td>
<td></td>
</tr>
<tr>
<td>2 850,1310,1550 nm laser source</td>
<td></td>
</tr>
<tr>
<td>2 Fiber optic power meter (multi wavelength)</td>
<td></td>
</tr>
<tr>
<td>2 Visible fault locator</td>
<td></td>
</tr>
<tr>
<td>2 HP Mini OTDR mainframe with floppy drive</td>
<td></td>
</tr>
<tr>
<td>4 cable: 2.2 km singlemode fiber reel connectorized at one end</td>
<td></td>
</tr>
<tr>
<td>1 cable: 300 m multimode cable</td>
<td></td>
</tr>
<tr>
<td>1 cable: 300 singlemode cable</td>
<td></td>
</tr>
<tr>
<td>2 3M mechanical splice tool</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 3: WDM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 each LiNiO2 Integrated Optical Modulators 1550 nm and 1310 nm</td>
<td></td>
</tr>
<tr>
<td>1 each Fiber coupled diode lasers, 1550 nm and 1310 nm</td>
<td></td>
</tr>
<tr>
<td>2 Fiber coupled high speed detectors with BNC adapter</td>
<td></td>
</tr>
<tr>
<td>2 HP arbitrary waveform generator</td>
<td></td>
</tr>
<tr>
<td>2 HP High speed digital storage oscilloscope</td>
<td></td>
</tr>
<tr>
<td>1 HP RF Spectrum Analyzer</td>
<td></td>
</tr>
</tbody>
</table>

The shared physics and electronics laboratories were clearly inadequate to house all the new equipment. An under utilized electronics laboratory was remodeled into classroom/laboratory space to house the program laboratories. Walls were painted dark charcoal gray and room darkening shades were purchased for the large windows. Movable wooden screens were built to serve as laser beam blocks. The adjoining faculty office allowed the classroom to be used between classes by students, who were encouraged to use the space to study, for internet access or to work on projects. Allowing students to use the classroom space to work together during their free time fosters a feeling of belonging. As one student stated, "We're the only program that has its own 'club house'." Nearby instructors are able to provide assistance when needed and ensure that rules are obeyed.

Fig. 1 Students practice fiber splicing and use of the OTDR in the Lightwave Communications Lab (1999)
2.2 Curriculum revisions

The original Photonics Steering Committee was reconstituted as the Photonics Engineering Technology Industry Advisory Committee. Meeting once a year, the committee members make suggestions to keep the curriculum relevant to current industry trends. Members also assist throughout the year by responding to requests for information used for accreditation reports and evaluations by the college. The committee has been an invaluable resource for school-to-career opportunities such as tours, speakers and internships, and its members have provided technical advice and assistance securing donations and other forms of support. At the October 1999 meeting, the Industry Advisory Committee endorsed the creation of an Advanced Laser Topics course to be taken by students during the last semester of the program. The course is used to explore topics of current interest and to give students the opportunity to work individually on projects such as building a CO$_2$ laser or assembling a fiber optic WDM system. An advanced course from the Electrical Engineering Technology was eliminated to add the course without increasing the number of credits.

Even before the telecommunications downturn, it was apparent that some students were excited by optics but not interested in the depth of electrical/electronics courses of the PET curriculum. The associate in applied science (AAS) in General Engineering Technology (GET) provided a suitable pathway for such students. The GET program consists of a core of math, science, technology and general studies courses with a concentration of four to five courses in an area of special interest. The four optics, laser and fiber optics courses, along with laser safety, were offered as a package of electives to GET students. Graduates of this "GET/Photonics Option" have similar employment and transfer experiences as graduates of the original PET program. The photonics option adds to the number of students in the PET program courses at a time when class size is closely scrutinized. All photonics related lab courses are restricted to 12-14 students, however, because of room size and safety issues.

2.3 Fiber optics certificate online

A one-semester Certificate in Fiber Optics Technology was proposed shortly after the PET program was approved in 1997. The certificate was intended to allow students to quickly enter the workforce and it provides an entry point for students who wanted to matriculate in the PET program but do not have the prerequisite math courses. In addition to a laser safety course, the certificate consists of two laboratory based technology courses, optics and fiber optics, and a telecommunications overview course. An elective course in mathematics or computer science is chosen for applicability to employment or to prepare students to enter an associate degree program. Politics within the Community College system prevented the certificate from being approved until the fall of 2000, at which point there was little demand for entry level fiber optics workers.

At the same time, the Connecticut Distance Learning Consortium was seeking certificate and degree programs to offer by distance learning via the Internet. Three Rivers received a $25,000 grant to adapt the Fiber Optics Certificate to distance learning. Professor Randall Seebeck was hired to create the curriculum for the fiber optic and telecommunications courses suitable for web-based delivery. A "math for optics" course was also created to provide students with a math refresher on the topics that would appear in future certificate courses. Additional support for curriculum development was provided by the Connecticut College of Technology: Curriculum Reform Project, a NSF-ATE grant to the CT Community College system's College of Technology program. The online certificate curriculum was subsequently adopted as a photonics option to the College of Technology associate degree in Technology Studies, which is available at all twelve of Connecticut's community colleges.

The telecommunications industry downturn has resulted in few traditional students registering for the certificate program, however, it has been used to deliver incumbent worker training to employees of JDS Uniphase (where one course was delivered by distance learning) and 3M Optical Systems. The 3M program is funded by a grant from the U.S. Department of Labor to the Connecticut Business and Industry Association. The innovative delivery involves company mentors who are available to assist with technical questions and motivate students who fall behind. The optics course, Introduction to Photonics, uses printed text and web applets as well as "home lab experiments" based on the OSA (Optical Society of America) Optics Discovery Kit. Students work at home or on the job in small groups to perform experiments such as measuring the index of refraction of gelatin cubes, exploring image formation with lenses, and determining the diameter of a hair by diffraction. The fiber optics course includes on-site laboratory experiments created by the instructor with the assistance of 3M. Traditional students are required to perform lab experiments at Three Rivers during a two day residency. Industry students have commented that although some of the labs are very similar to what they do on the job, the course has given them an understanding of what they do and why they do it.
2.4 Project PHOTON

In 2000, the New England Board of Higher Education received funding for PHOTON, a professional development, curriculum enhancement and laboratory improvement project funded by the National Science Foundation Advanced Technology Education program. The authors of this paper are Principle Investigator (JD) and a participant (RS) in project PHOTON, which has allowed Three Rivers to tap into a New England-wide network of educators and industries. PHOTON has benefited the Three Rivers Photonics program in many ways.

- NEBHE marketing and dissemination efforts for PHOTON include the College and its participants, increasing the PET program visibility
- Curricula developed for PHOTON (text and laboratory experiment manual) are in use at the College.
- The College received a PHOTON lab kit (half the cost paid by the grant), which has been used both on campus and for various training programs off-campus.
- Members of the PHOTON Industry Advisory Committee have also assisted the college in obtaining donations, and providing technical support and assistance.

3. Growing in decline: 2001-present

3.1 Curriculum changes adapt to changing conditions

After a surge in enrollment in the first three years, the number of students in the Photonics Engineering Technology program began to drop; fewer than 10 new students enrolled in Fall 2002. Several factors have contributed to the loss of students, including news media proclamations that “fiber optics is dead” and the loss of the JDS Uniphase-sponsored scholarship for photonics students. A more fundamental problem is that the word “photronics” is unknown to most high school students and their parents. If students have heard the term, they tend to associate it with optical fiber and telecommunications. An informal survey of 25 students attending the vocational-technical high school next door to the college revealed that not one student could define the term and most had never heard of it.

While the fiber optics industry awaits resurgence, Connecticut has seen growth in other areas of photonics. Companies producing industrial lasers and laser systems and precision optics as well as laser job shops have been seeking new employees in recent months. PET graduates have also found employment in the lighting industry. In response to changing employment opportunities and to give students a broader look at the industry, the PET curriculum underwent the third modification in its five year history in 2001-2002. A course in Laser Electronics was added, replacing the more generic Electronics II and allowing better integration of optics and electronics courses. Two required courses, Digital Electronics and Calculus II, were replaced by a technical elective and a math/science elective respectively. This affords students the opportunity to tailor the program to their own interests and to take courses such as CAD or manufacturing processes, and to study chemistry or statistics.

The final curriculum change, to be effective Fall, 2003, is the reorganization of the first two semester of optics, formerly Geometric Optics and Wave Optics. The new courses, Introduction to Optics and Applied Optics, cover the same material as the previous courses, but the first semester includes interference, diffraction, polarization and sources of light, providing a broader view of the subject. Removing more intensive topics such as matrices and aberrations to the second semester allows students to begin the program at a lower math level. The course will also be more appealing as a technical elective to students in other programs. The Photonics Engineering Technology curriculum is shown in Table 2. Developmental courses in Math and English are not indicated, but may be required after admissions placement testing.

In addition to changes to make the Photonics Engineering Technology degree more flexible and attractive to students, a Photonics/Electrical Engineering Technology double major was created allowing students in either program to receive both degrees taking only four additional courses. For students who earn Tech Prep college credits while in high school, both degrees may be earned in two years.

3.2 Laboratory expansion

Program graduates working in industry increasingly reported that they were expected to be knowledgeable about various instruments and procedures that had not been addressed in their laboratory courses. A new proposal to NSF was designed to address this situation. In January 2002, a $43,000 grant was received from the Course, Curriculum and Laboratory Improvement program (NSF-CCLI) for the development of an advanced laboratory for lightwave communications. The CCLI grant builds on the earlier ILI grant that established the Lightwave Communications Laboratory. Instrumentation specified in the CCLI proposal includes an optical spectrum analyzer, single mode lasers, modulators and WDMs, and an EDFA experimentation kit.
Table 2. Suggested plan of study for Photonics Engineering Technology students, Fall 2003

<table>
<thead>
<tr>
<th>Course number/name</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHO 105 Laser Safety</td>
<td>0.5</td>
</tr>
<tr>
<td>PHY 140 Introduction to Optics/Lab</td>
<td>4</td>
</tr>
<tr>
<td>EET 1100/1 Circuits I/Lab</td>
<td>5</td>
</tr>
<tr>
<td>MATH 141 Precalculus</td>
<td>4</td>
</tr>
<tr>
<td>ENG 111 College Composition</td>
<td>3</td>
</tr>
<tr>
<td><strong>Semester I total</strong></td>
<td>16.5</td>
</tr>
<tr>
<td>PHY 141 Applied Optics/Lab</td>
<td>4</td>
</tr>
<tr>
<td>EET1101/1 Circuits II/Lab</td>
<td>4</td>
</tr>
<tr>
<td>EET1120/1 Electronics I/Lab</td>
<td>4</td>
</tr>
<tr>
<td>MATH 151 Calculus I</td>
<td>4</td>
</tr>
<tr>
<td>ENG 122 Writing in the Workplace</td>
<td>3</td>
</tr>
<tr>
<td><strong>Semester II total</strong></td>
<td>19</td>
</tr>
<tr>
<td>PHO 230 Laser Electronics/Lab</td>
<td>4</td>
</tr>
<tr>
<td>PHO 240 Introduction to Lasers/Lab</td>
<td>4</td>
</tr>
<tr>
<td>Math/Science Elective</td>
<td>3</td>
</tr>
<tr>
<td>Humanities elective</td>
<td>3</td>
</tr>
<tr>
<td>Technical Elective</td>
<td>3-4</td>
</tr>
<tr>
<td><strong>Semester III total</strong></td>
<td>17-18</td>
</tr>
<tr>
<td>PHO 250 Fiber/ Integrated Optics/Lab</td>
<td>4</td>
</tr>
<tr>
<td>PHO 290 Advanced Laser Topics</td>
<td>3</td>
</tr>
<tr>
<td>EET 2140/1 Telecomm. I/Lab</td>
<td>4.5</td>
</tr>
<tr>
<td>Social Science elective</td>
<td>3</td>
</tr>
<tr>
<td><strong>Semester IV total</strong></td>
<td>14.5</td>
</tr>
</tbody>
</table>

The telecommunications industry downturn has had an unexpected bright spot; laboratory equipment and instrumentation is inexpensive and companies find tax deductible donations to the College attractive. Due to a state budget crisis and severe cuts to the college budget, the college was unable to make a cash match to the equipment portion of the grant. However, the industry downturn resulted in large donations from downsizing companies, including two complete fiber optics workstations, two Newport fiber optics education kits, and two Newport optics education kits from JDS Uniphase. In addition, once prohibitively expensive components are available through Internet auction and surplus sites at pennies on the dollar. The combination of declining prices for instrumentation and donations from industry have allowed the project to complete purchase of all the requested equipment as well to purchase additional tools and inspection instruments to supplement the original lightwave lab.

Fig. 2 Students use the optical spectrum analyzer to study laser modes in the Advanced Lightwave Communications Lab (2003)
Table 3 lists the equipment purchased (or in some cases donated) for the advanced lightwave communications laboratory. Three stations are specified, and students rotate through the experiments. While the overall curriculum is still a work in progress, students in Advanced Laser Topics have worked with the optical spectrum analyzer to observe spectra of laser and LED sources; experiments with the EDFA kit and DWDM station are currently under development. When completed, lab experiments will be on the PET program web site, linked from the college web site (www.trcc.commnet.edu).

<table>
<thead>
<tr>
<th>Station 1: passive components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Agilent Optical Spectrum Analyzer with white light source and wavelength calibrator</td>
</tr>
<tr>
<td>1 fiber coupler</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 2: active components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Opto Sci EDFA laboratory kit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station 3: DWDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 each JDSU DFB lasers 1338 nm and 1358 nm</td>
</tr>
<tr>
<td>2 WDM coupler</td>
</tr>
<tr>
<td>2 laser butterfly mount</td>
</tr>
<tr>
<td>2 fiber coupled detector</td>
</tr>
<tr>
<td>2 TE cooler</td>
</tr>
<tr>
<td>2 LD driver w/cable</td>
</tr>
<tr>
<td>2 Agilent Arbitrary Waveform Generator</td>
</tr>
<tr>
<td>2 Agilent 100 MHz oscilloscope</td>
</tr>
</tbody>
</table>

The acquisition of additional workstations meant the PET program was again in need of additional laboratory space. A third laboratory was created to house the equipment for the advanced lightwave laboratory. The new Lightwave Communications Laboratory is next to the original photonics laboratory, now called the "Laser/Optics Lab". The two are connected by a stockroom, which houses electronic and fiber optics supplies. The new space is shared with the electrical engineering technology program, which uses it for a lab courses in telecommunications. Since the laboratory workstations are on wheels, instructors have flexibility in setting up the lab for each group of students.

4. Marketing and recruitment

By the time the third class of photonics technicians graduated in 2001, the first graduates were already being downsized from their telecommunications related jobs. The challenges to the program in the past two years have been to broaden the curriculum to include more laser physics and applications, increase the variety of hands-on laboratory experiences, and to attract increasingly skeptical students. The first two challenges have been well addressed, but the third remains elusive. "Evangelists for optics", the Photonics Engineering Technology faculty feels that once students have seen a little of the subject, they will want to know more. The time to introduce students is at the start of their high school career (or even earlier) so they can take appropriate math and science courses that will lead to college success. Initiatives to introduce high school students to optics include:

- Development of Tech Prep 2+2 agreements with area high schools. The first such program will begin with Plainfield (CT) High School, a PHOTON participating institution, in Fall 2003. Plainfield High School students will receive up to 14 college credits for completing a program that includes math through Algebra II, English communications, physics and Introduction to Optics.

- Creation of scholarships for photonics students. The College has received grants from SPIE for the past two summers, allowing high school students to explore photonics technology by taking Introduction to Photonics. Approximately $4300 pays for tuition, fees, books and supplies for up to 10 students taking the four credit laboratory course. Three of the 10 students from the Summer 2002 scholarship group are now enrolled full time in the Photonics Engineering Technology program. Additional scholarship assistance is being sought from both...
funding agencies and industry. For Fall 2003, scholarships were made available to Three Rivers photonics students from the NSF Computers Science, Math, and Engineering Scholarships (NSF-CSEMS) grant awarded to the Community College system's College of Technology. Four new students will enroll in this program, which seeks to increase the number of science, math, engineering and technology students graduating from two and four year programs. Scholarships not only increase the number of students attending college, but also create marketing opportunities for the Photonics program.

- Aggressive recruitment of new students, aided by the college’s SPIE student chapter's educational light show. A member of the faculty or a student volunteer attends each of the college's tech nights and college fairs, and high school teachers receive mailings throughout the year inviting them to bring student groups to visit the laboratories. Although it is a fairly simple matter to interest students in optics/photonics, convincing parents that the program will lead to a career is a more difficult challenge. New marketing materials being developed emphasize "pathways" available to our graduates, including transfer to four-year programs as well as immediate employment. Figure 3 shows the College's "rivers" logo incorporated into the pathways theme on a new program brochure. The new brochure also refers to Laser Optics Technologies, which include the degree programs in photonics and general engineering/photonics. The term "photonics" is introduced and defined inside the brochure.

The new strategies have resulted in increased enrollment of day students in 2003. The day program tends to attract younger students who are recent high school graduates. Typically these students are more interested in transfer to a four-year university and less reluctant to relocate for employment than older students, who most often are interested in finding local employment after graduation. A significant increase in the evening student population is not expected until the employment situation improves.

5. Conclusion

Three Rivers Community College has successfully implemented an associate in science degree program in Photonics Engineering Technology and a photonics option to an associate in applied science degree in General Engineering Technology. Long term success of the program depends on the ability to attract new students in sufficient numbers. Increasing curriculum flexibility and emphasizing transfer agreements with four-year colleges and universities are strategies designed to attract and retain students while the industry remains sluggish. It is hoped that when the industry recovers, the Photonics Engineering Technology program will be well situated to provide technicians to support the photonics companies of southern New England and beyond.
5. References
1 National Photonics Skills Standard for Technicians, Center for Occupational Research and Development, CORD, Waco, TX, 1995.

6. Acknowledgements

FOTEP
Funded in-part by the Advanced Technological Education program of the National Science Foundation (#ATE 9553762). Principal Investigator, Nicholas Massa, Springfield Technical Community College; Co-Principal Investigators Fenna Hanes (Project Manager), New England Board of Higher Education; James Masi, Western New England College; David Maack; Consultant Elias Awad, Wentworth Institute of Technology.

NCTT
Funded in-part by the Advanced Technological Education program of the National Science Foundation (#ATE 9751990). Principal Investigator, Founding Principal Investigator, James Masi, (retired); Executive Director Gordon Snyder, Springfield Technical Community College; Co-Principal Investigators Nicholas Massa (returned to faculty assignments) Springfield Technical Community College; Fenna Hanes, New England Board of Higher Education; Gary Mullet, Springfield Technical Community College.

PHOTON
Funded in-part by the Advanced Technological Education program of the National Science Foundation.(ATE #ATE 0053284) Principal Investigator, Judith Donnelly, Three Rivers Community College; Co-Principal Investigators Fenna Hanes (Project Manager), New England Board of Higher Education; John Swienton, Exfo USA, Inc.; Senior Personnel Nicholas Massa and Barbara Washburn, both Springfield Technical Community College.

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Education and training in preparation of rare-earth doped optical glasses

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Abstract: For the first time in Taiwan, we have established an undergraduate training program for optical glass melting and applications. Incorporated with e-learning, we try to make the learning process and hands-on practice in preparation of optical materials more happy and efficient. Some ideas for course design, revised facilities and teaching tools have been proposed.

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OCIS codes: (160.2750) Glass and other amorphous materials; (140.3510) Lasers, fiber

1. Introduction
Rare-earth doped optical glasses have been widely used in opto-electronic devices and optical communication systems. Although glasses can be prepared by a wide variety of methods, the majority are still made by melting of batch components at high temperatures. The melting process mainly involves the selection and calculation of raw materials in a batch-basis, mixing of these materials, dehydration and thermal decomposition of the metallic salts, melting the batch materials to obtain homogeneous liquid, and finally quenching the liquid to obtain glasses. Conversion of the high temperature melt into a homogeneous liquid requires to remove unmelted remnants, impurities, and bubbles. The melting process determines the quality of the glasses and should be treated as a key issue in the production of rare-earth doped optical glasses. In particular, when undergraduate students take the course of glass technology and its laboratory practice, it is recommended to show the students how and what has happened in a glass melting furnace. For these reasons, a continuous glass melting furnace with a sloping flow-channel in a laboratory scale has been designed for students to learn how to prepare high quality optical glasses. The objective of the course is to help students learning i) how to select raw materials, ii) how to design a glass melting furnace, iii) how to operate and control the glass melting process, iv) how to remove bubbles from the glass melts, and v) how to eliminate the thermal stress in a quenched glass sheet.

At NUU, we have also established fiber-drawing facilities, glass extrusion molding machine, glass rod pull-up system, and glass lathe lamp work equipments. However, we will focus on the introduction of the sloping channel glass melting furnace as a useful teaching tool in glass workshop.

2. Course design
The course for rare-earth doped optical glasses is categorized into three parts:
i) the physical phenomenon of rare-earth ions interacted with amorphous oxides, including silicates, borates and phosphorous glasses;
ii) design and operation of a continuous glass melting furnace with a sloping channel, including how to remove impurities and bubbles; and
iii) characterization techniques of the rare-earth doped glass samples.

3. Design of the continuous glass melting furnace with a sloping channel
The furnace is a continuous type furnace with SiMo heating elements and maximum operation temperature is around 1550°C. As shown in Fig. 1, the left part of the furnace is similar to a conventional tank furnace used in the glass melting factories. However, the right part is designed on purpose in a sloping manner for bubble removal. And it works well. The principle that an inclined surface can help removing bubbles form glass melts is based upon the Stoke’s law:

\[ V_b = \frac{d_b^2 g (\rho_l - \rho_g)}{18 \mu} \]  

where \( V_b \) is the floating speed of a spherical bubble, \( d_b \) is the diameter of the bubble, \( g \) is gravity, \( \rho_l \) and \( \rho_g \) are the densities of liquid and vapor, respectively. \( \mu \) is the viscosity of the fluid. Thus, the time for a bubble to float through a liquid layer of depth \( H \) may be calculated by

\[ t_b = \frac{H}{V_b} \]
Because of $p_{g} \rightarrow \rho_{l}$, therefore the time required to remove those bubbles of diameters greater than $d_{B}$ will be

$$t \rightarrow t_{B} = \frac{18\mu H}{d_{B}^{2} g \rho_{l}}$$

(3)

When glass melts flow over an sloping surface with an inclined angle of $\theta$, eq. (3) may be modified into

$$t_{B} = \frac{18\mu H}{d_{B}^{2} g \rho_{l} \cos \theta}$$

(4)

and

$$d_{B}^{2} = \frac{18\mu_{v}}{g \rho_{l} \cos \theta LW}$$

(5)

where $q_{v}$ is the volume flow rate of the glass melts (m$^{3}$/s), $W$ and $L$ are the width and length of the sloping channel, respectively. Based upon eq. (5), bubbles with diameters larger than $d_{B}$ will be removed by the sloping channel design.

Schematic illustrations of the continuous glass melting furnace with sloping channel are shown in Figs. 1-4. A simulated furnace has also been constructed for students to practice before they really start to operate the actual furnace, and simulation of the melting process is part of the e-learning program of the course.

Fig. 1 Schematic illustration of a continuous glass melting furnace with sloping channel structure
A course and glass melting facility has been developed and rare-earth doped glasses have been successfully prepared. Simulation of the furnace has been incorporated into the course as part of the e-learning program.
Teaching fiber-optic communications in engineering technology programs by virtual collaboration with industry

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Abstract: A fiber-optic communications course requires a deep understanding of the physical processes of the components and systems. Unfortunately, many students in engineering technology programs lack the scientific background for such a course. Another challenge is that these students need to be trained as maintenance and control personnel. To resolve these problems, we focus our teaching on the use of corporate technical documentation.

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OCIS codes: (000.2060) Education; (060.2330) fiber optics communications

1. Fiber-optic communications courses and engineering technology programs

Fiber-optic communications has become the linchpin of the modern telecommunication industry. In fact, more than 98% of U.S. domestic traffic uses fiber cable. This is why more and more engineering technology schools offer a variety of courses related to fiber-optic communications. Since fiber-optic communications technology includes both component and networking aspects, such courses have to lean on knowledge that students have gathered in physics, mathematics, electronics, telecommunications, and other engineering and science courses. However, analysis of fiber-optic technical documentation relies not only on broad education but also on specific knowledge acquired through the study of fiber-optic technology.

Another important feature of fiber-optic communications technology is that it changes very rapidly. Every day brings new developments in components, networking, and even business conditions. These developments can be as simple as some improvements in the characteristics of a component, a new design in the architecture of a specific network, or an increase in production by a specific company. But these developments can also be the invention of new devices, such as erbium-doped or Raman fiber amplifiers; new transmission technology, such as wavelength-division multiplexing; or a new approach to networking, such as the all-optical network. From the business standpoint, one has to read the professional journals every day to follow mergers, acquisitions, and spinoffs. Hundreds of start-up companies appear and disappear and well-established companies change their names and profiles. Thus, teaching a fiber-optic communications course requires a permanent updating of the lecture material and laboratory exercises, which means bringing breaking industry developments into the classroom and laboratory.

Therefore, teaching a fiber-optic communication course presents a challenge. On the one hand, it should provide deep academic knowledge about the subject. On the other hand, the subject itself changes so rapidly that classroom-acquired knowledge becomes outdated before students reach the workplace. The solution lies in finding the right balance in providing fundamental knowledge and teaching the current technology. This is where close collaboration with industry has to come into the play.

When teaching in an engineering technology program, the instructor must address two critical issues: The first is the background in the basic sciences of students in engineering-technology programs. Typically, their mathematical education doesn’t include courses beyond Calculus II, and their education in the physical sciences doesn’t exceed two courses in non-calculus physics. The problem is the scientific descriptions of processes, devices, and systems that have to be learned require a thorough grounding in the fundamentals of mathematics, physics, and other disciplines. A fiber-optic communications course is particularly challenging because it relies heavily on a deep understanding of the physical processes that control the behavior of the components and systems constituting this technology. Optical fiber itself, light sources, photodiodes, and all the passive and active components of fiber-optic networks demand an in-depth knowledge of classical optics, semiconductor materials, micromechanical and micro-optical processes, and many aspects of modern science.

The second point is the nature of the future work and potential responsibilities of the graduates of engineering technology programs. They are trained to work as technologists, which means their major
responsibilities lie mostly in maintenance and control; however, the tendency is to involve them in design, development, and research. Thus, their academic training has to provide them with a deep knowledge of technology coupled with a sound general education. This knowledge entails a complete understanding of corporate technical documentation, particularly, company specifications sheets. Thus, again, engineering-technology education must rely heavily on exposing students to industry practice, which can only be achieved by collaboration with industry.

There are many forms of collaboration between academy and industry most of them requiring the physical presence of students at company workplaces. Unfortunately, this requirement is often difficult to meet and the effectiveness of the student at the work site is always questionable. This is why we propose a virtual collaboration with industry without the need for the physical presence of the student at the workplace. This type of collaboration introduces industry practice in the academic environment. To implement this type of collaboration, we bring two key elements of industry practice to the classroom. First, we simulate a realistic working environment in our teaching. Secondly, we use corporate technical documentation, especially the manufacturers’ specifications sheets, as a teaching material.

The following two examples demonstrate our approach to virtual collaboration with industry in the laboratory and classroom in our fiber-optic communications course at the senior level in our undergraduate telecommunications-technology program.

2. Measuring attenuation of a multimode fiber (MMF) in the laboratory

Here we want to measure attenuation of an MMF. The main point is to investigate how the main performance characteristic of an optical fiber—attenuation—depends on the length of a fiber-optic communications link.

Attenuation is the first characteristic of any transmission medium that a telecommunications engineer will be looking at when choosing a link. In fact, optical fiber found application as a practical transmission medium only when its attenuation was reduced to the current number, about 0.2 dB/km. Thus, understanding attenuation is a critical point in studying the properties of an optical fiber. Attenuation in MMFs is particularly interesting because, in contrast to attenuation in singlemode fiber (SMF), this attenuation changes with a change of the fiber length, which is the only proof of the existence of modes in optical fiber.

The main feature of our laboratory exercises is that we try to conduct them the same way engineers carry their projects out in the workplace.

Each experiment is designed as a realistic working assignment, which means that only the goal to be achieved through the experiment and some preliminary information are all the information provided. The student is given no detailed step-by-step instructions. Using their knowledge of the topic obtained in the classroom and from the textbook [1], the student has to devise by himself or herself the arrangement and the procedure of measurement and realize what data are to be gathered and how that data must be processed. The student has to build the setup of the experiment and the necessary circuitry and perform the measurements.

As an example of the implementation of this approach, let’s consider the following laboratory exercise: The underlined text shows what the students receive as a part of their laboratory manual. This portion of the manual represents the students’ assignment. Text in italics shows how the assignment should be carried out, which includes the reasoning and practical steps that have to be developed.

Experiment 1. Measuring attenuation in optical fibers

Equipment: IF-97 ED, WL-850 calibrated light source, cables of SuperEska plastic optical fiber, cables of silica optical fiber by Siecor, a trainer board, resistors, and a power meter

Assignment: Collect data to evaluate attenuation of multimode optical fiber

Implementation:

First, students become familiar with all equipment provided. They learn how to use a trainer board, a power meter, and a calibrated light source. They become familiar with the characteristics of all the devices by studying the technical documentation (data sheets), which are part of the laboratory manual. For example, they find out that a power meter can measure over a certain range of wavelength, namely, 650 nm, 850 nm, and 910 nm. Secondly, it is expected that the students will develop the following reasoning:

1. Attenuation is given by [1]

   \[ A \text{ (dB/km)} = - \text{Loss (dB)} / \text{Fiber length (km)}, \]  

   (1)
where $\text{Loss (dB)} = 10 \log \frac{P_{\text{out}} (\text{mW})}{P_{\text{in}} (\text{mW})} = P_{\text{out}} (\text{dBm}) - P_{\text{in}} (\text{dBm})$

Therefore, to obtain the attenuation, we need to measure output and input power either in mW or in dBm.

2. Input power, $P_{\text{in}}$, is not the power radiated by a light source, but it is the power launched into an optical fiber. Therefore, if we measure the light power emerging from a short piece of optical fiber, we will obtain the desired quantity, $P_{\text{in}}$. This is because the losses introduced by this short piece are negligible.

3. Output power, $P_{\text{out}}$, is the light power emerging from the optical fiber under test. Thus, to obtain attenuation, we need to measure $P_{\text{in}}$, $P_{\text{out}}$, and the fiber length.

4. It follows from the definition of attenuation that $A$ (dB/km) should be independent of fiber length. However, this is not true for multimode fibers. To investigate this phenomenon, we need to take measurements of attenuation with fiber cables of various lengths.

5. Thus, we arrive at the following procedure for the experiment [2]:
   - Choose a light source after looking at the specifications sheets of a light source and a specific optical fiber.
   - Measure the light power emerging from a short piece of optical fiber.
   - Measure the light power emerging from multimode optical fiber cables of different lengths.
   - Record the length of each fiber cable.

Each student has to write an individual laboratory report. This paper is considered as a technical report that the student would have to submit to his or her potential supervisor after completing an assignment in the workplace. Writing this report requires the students to express their thoughts in a professional manner, with an emphasis on appropriate grammar and style.

The laboratory manual includes guidelines and report requirements. These requirements emphasize that the report must provide enough information to enable anyone to reproduce the reported measurements. A theoretical discussion must be included in the report and it must contain the qualitative predictions of the expected results of the measurements. Another important consideration is analysis of the results. For example, the student must compare the results obtained with the theoretical predictions and with the characteristics given in the manufacturer’s data sheet. In our example, that is, Experiment 1, the values of attenuation computed from the measured losses must be compared with the attenuation given in manufacturer’s data sheet attached to the laboratory manual. The analysis must include a discussion of any discrepancies among theory predictions, the manufacturer’s data, and the results of the actual measurements.

What follows is the reasoning that we expect the students will express in the theoretical section of their laboratory report:

**Attenuation** was introduced by the fiber-optics communications industry in order to obtain a real measure of a fiber’s quality. Indeed, absorption, scattering, and bending cause the loss of optical power inside an optical fiber. Therefore, the longer the fiber, the greater the absorption, scattering, and bending losses are while a light beam propagates through the fiber. In other words, the longer the fiber, the greater the losses. Thus, if we divide the value of the fiber’s losses by length, we obtain the characteristic that really describes the loss property of a fiber, regardless of its length. Attenuation, as follows from the above consideration, should be independent of fiber length; that is, it should be constant. In fact, manufacturers’ data sheets show only one value for attenuation.

However, if we take into consideration the existence of modes in a multimode optical fiber, we will arrive at a conclusion other than the one noted above because different modes travel significantly different distances within the same fiber. In other words, even though the length of a fiber is the same for all modes, the traveling distance is quite different for the various modes. Since high-order modes travel significantly longer distances within the same core than their low-order counterparts, they experience much more absorption, scattering, and microbending events, which results in greater losses for such modes. The result, then, is that high-order modes disappear much faster than low-order modes. Therefore, our conclusion is this: The longer the fiber, the fewer the number of modes arriving at the receiving end.

For a very long fiber, this process reaches the steady-state condition called equilibrium-mode distribution, meaning that only low-order modes continue to propagate inside a long optical fiber. But these modes experience less loss than their high-order counterparts simply because they travel a shorter distance within the fiber. Therefore, for a short piece of optical fiber, where all modes exist, we will measure the higher level of loss, while for a longer
piece of fiber, where only low-order modes are left, we will measure the lower level of loss. In other words, for multimode fiber, attenuation should decrease with an increase in fiber length.

If we compare graphs of attenuation versus fiber length for MMF and for singlemode fiber (SMF), we should see that for an SMF, attenuation should be constant whereas for MMF, attenuation should decrease over the fiber length. We need to understand that this experiment proves the existence of modes in optical fiber and that there are no direct measurements that can prove this existence because we can’t look inside a fiber.

In addition to the above reasoning, the students have to describe in their laboratory reports the industry approaches to these measurements. They have to find out, for instance, that there is a method of measuring attenuation defined in a fiber-optic test-procedure (FOTP) standard accepted by the Electronic Industry Alliance (EIA) and the Telecommunications Industry Association (TIA). They also have to analyze the difference between their measurements and those performed in accordance with this standard.

We take a similar approach we assign our students the task of explaining how attenuation in optical fiber depends on the wavelength of a light source. Here the students have to use the graph “Attenuation vs. wavelength” given in a manufacturer’s data sheet. They have to analyze this graph (“the longer the wavelength, the smaller the attenuation”) and explain that it is the absorption that determines the course of this graph.

3. Discussion of fiber-bandwidth theory

Here we want to investigate the bandwidth (transmission capacity) of an optical fiber. The objective is to develop a scientific understanding of this performance characteristic of the optical fiber given in the manufacturer’s data sheet during a classroom discussion of fiber-bandwidth theory.

Bandwidth is the second basic characteristic of a transmission link. Optical fiber has become the dominant transmission medium simply because it has the largest bandwidth among all other existing media. This is the major advantage of an optical fiber over a microwave link, a coaxial cable or a copper wire. The theoretical limit of the bandwidth of optical fiber is about 50 Tbit/s; however, a close look reveals a number of obstacles that restrict this bandwidth to a much lower number. The study of bandwidth inevitably brings students to a discussion of dispersion.

Intermodal and chromatic dispersions are discussed based on the physical processes of light propagation within an optical fiber. This discussion is followed by a consideration of how these dispersions affect the bandwidth (bit rate) of an optical fiber.

The study of this topic is concluded by a review of a data sheet of an optical fiber. For our class discussion, the specifications sheet from Plasma Optical Fibre Company (given in the textbook) is used; as homework, students are assigned to review the latest data sheets from different manufacturers (Corning, Lucent Technologies, Pirelli, SpecTran, and others). The formats and examples of such specifications sheets are presented in the course textbook.

This is what we expect students to learn as a result of our consideration of the bandwidth theory of a multimode optical fiber given in a manufacturer’s data sheet:

- The manufacturer specifies bandwidth as a set of numbers at different wavelengths. These numbers are given even without units. For example, the data sheet says that the bandwidth of MMF at 850/1300 is equal to 200/400. The problem is to analyze these data.

First, since bandwidth is restricted by intermodal and chromatic dispersions and since intermodal dispersion puts severe limitations on bandwidth, we must conclude that this specification is determined by intermodal dispersion. Here we need to recall that intermodal dispersion is the phenomenon leading to the spread of the output pulse. This widening stems from the fact that light inside a fiber breaks down into separate discrete beams called modes. These beams travel at different angles with respect to the fiber’s centerline; therefore, they arrive at the receiver end at different times. The output pulse is composed of the small pulses delivered by the individual modes. Thus, the front edge of the output pulse is determined by the fastest mode, while its rear edge is determined by the slowest mode. This is why the output pulse is spread in contrast to the input pulse.

Secondly, bandwidth, as already noted, is specified in a data sheet without mention of its units. This raises the question of how manufacturers measure fiber bandwidth. We find out that manufacturers specify bandwidth-length product rather than pure bandwidth, which means that they use MHz-km rather than MHz.

Third, to understand why manufacturers specify bandwidth as two numbers, we need to consider what essentially changes in optical fiber with a change in operating wavelength. The first—and the main—reason for the change is that the number of modes, N, depends on the wavelength. Indeed, this number is given as

\[ N = \frac{V^2}{2} \text{ or } N = \frac{V^2}{4}. \]
where

\[ V = \left( \frac{\pi d NA}{\lambda} \right) \]  

(3)

Here \( d \) is the core diameter, \( NA \) is the numerical aperture, and \( \lambda \) is the operating wavelength [1]. From these calculations we come to the conclusion that the shorter the wavelength, the greater the number of modes within a fiber and the wider the pulse spread caused by intermodal dispersion and, therefore, the lower the bandwidth.

The second reason for the change is that chromatic dispersion depends on the wavelength. In fact, pulse spreading caused by chromatic dispersion can be calculated as follows:

\[ \Delta t_{\text{chrom}} = D(\lambda) \Delta \lambda L, \]  

(4)

where \( D(\lambda) \) is the chromatic-dispersion parameter measured in picoseconds (ps) per nanometer (nm) times kilometer (km), \( L \) is the transmission length in km, and \( \Delta \lambda \) is the spectral width of the light source in nm. Given the spectral width of the light source and the transmission length, the chromatic-dispersion parameter becomes the critical characteristic of an optical fiber that determines chromatic dispersion. Manufacturers specify the chromatic-dispersion parameter of optical fibers either by giving its value or by the formula

\[ D(\lambda) = \left( \frac{S_0}{4} \right) \lambda \left[ 1 - \left( \frac{\lambda_0}{\lambda} \right)^4 \right], \]  

(5)

where \( S_0 \) is the zero-dispersion slope in ps/(nm\(^2\)-km), \( \lambda_0 \) is the zero-dispersion wavelength, and \( \lambda \) is the operating wavelength. Thus, we can see why the bandwidth depends on the wavelength: Bandwidth depends on pulse spread; pulse spread, in turn, depends on chromatic dispersion; lastly, chromatic dispersion depends on the wavelength.

This is the kind of discussion students have to present in their term papers; they also have to be ready to demonstrate such knowledge on examinations.

The above examples show how we arrange virtual collaboration with industry. Our experience shows that such an approach can be very successful when teaching fiber-optic communications at the senior level in the undergraduate telecommunications engineering technology program.

4. Summary

The main challenge in teaching a fiber-optic communications course—where the subject matter is the physical processes of components and systems—in engineering technology programs is the limited scientific background of the students. Also, it is important for engineering technology programs to simulate collaboration with industry so that students gain "real-world" experience even before they start their professional career.

To accomplish this, we propose adoption of a program we call virtual collaboration, in which the teaching process simulates the true-to-life working environment and the teaching material relies heavily on real technical documentation, such as specifications sheets and technical notes.

Such an approach would entail, for example, the use of the specifications sheets of a multimode optical fiber (MMF). Through discussion of MMF attenuation, an understanding of the mechanisms of losses within an MMF should convince the students that (a) attenuation should be independent of fiber length, although the existence of modes will result in decreasing attenuation with length; and (b) attenuation depends on the wavelength of the transmitted signal. To verify these facts, the students should be able to develop the test procedure and perform measurements in the laboratory.

Bandwidth (transmission capacity) is the second basic characteristic of a transmission link. Understanding the theory of dispersion allows students to comprehend why real MMF bandwidth is restricted to 200/400 MHz-km at 850/1300 nm, as given in a typical data sheet. By working out simple formulas involving the relationship of the number of modes to the operating wavelength and dependence of chromatic-dispersion parameter on the wavelength, students are able to discern why manufacturers specify bandwidth at each \( \lambda \).

References:

The Global Photonics Education Network:  
Another Way to Think Globally and Act Locally 

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Abstract: As the world gets smaller through globalization and telecommunication, it also gets richer in possibilities. Empowering the educators to exchange ideas on successes and mistakes continually on the global stage while working to improve the education on their local stages can galvanize those potential richness. Our goal is to enhance this global inter-connectedness by facilitating the local intra-connectedness among the regional educators and their organizations, which can form local education clusters.  
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1. Introduction 

We live in a time when there are such astounding telecommunications tools (from telephones to the World Wide Web) that there should never be any more need to re-invent the wheel. If these tools can be used to their fullest, once new knowledge is generated it can be disseminated for all to implement in ways best adapted to their particular location, situation and need. It is imperative to apply this principle to education throughout the world. Without higher education, one cannot participate fully in today’s knowledge economy. Higher education is often too expensive: only 1/3 of the population can afford it, even in most developed countries. Physical infrastructure does not exist to accommodate the other 2/3 of the population. Even if the infrastructure were to be created, the cost would skyrocket. Without a much larger base of educated people, the global knowledge economy cannot grow in a sustainable way.  

A key sector that in many ways epitomizes the knowledge economy is the photonics industry. Let us develop a system for knowledge creation, organization and delivery of optics/photonics education and training that is economically accessible and functionally evolutionary. Just as the brain is made of interconnected individual neurons that become greater together than the sum of their parts, we can establish a global network that interconnects photonics educators in a way that enhances their work at a local scale through interacting with their peers globally. The end-result should be a net increase in the quality and quantity of good photonics education material and delivery worldwide, with a decrease in overall cost. This will make photonics education and training available to more people – including some who could not otherwise afford it – in more interesting ways.  

The model on which this Global Photonics Education Network can be built, at least when it comes to its infrastructure, is that of clusters. “Clusters” are local organizations regrouping people with common goals with a desire to band together to forward these goals, still allowing them to compete in the global market. It is a well-known model in the business world, well analyzed by Michael Porter of Harvard Business School and applied to the photonics industry sector by Robert Breault of Breault Research Organization. Each local cluster often establishes links with other like-minded clusters from other parts of the world and “clusters of clusters” can be formed, enhancing the effect of the local clusters (getting better deals from suppliers, affecting political decisions, influencing financial laws...). Such a model can be developed – and is in fact currently being developed – for photonics education and training. Examples of local photonics education clusters include the Ontario Photonics Education and Training Association (OPETA) in Ontario, Canada, the National Alliance for Photonics Education and Training (NAPET) in Singapore). We should encourage the formation of other local clusters around the world and provide the overarching “cluster of clusters” through the Global Photonics Education Network (GPEN). The modern cluster concept is an excellent example of “think globally, act locally”, advised by Buckminster Fuller. It is philosophically inspiring and, yet, a pragmatic methodology for building stable and sustainable global economy.
1.1 Why Optics/Photonics?

Since ancient times, a large number of the conceptual breakthroughs in science and technology, promoting our material (economic) well-being, are being facilitated by optics (and photonics). Early astronomy and the discovery of telescopes led us to appreciate the significance of adopting the Helio-centric philosophy and reject the Earth-centric, anthropo-centric path, and opened our minds to explore the vast, cosmic universe. The discovery of early microscopy opened up the floodgates to explore the microscopic wonders behind the diverse, terrestrial bound, living universe. During the last couple of centuries, studies on spectrometry, characteristic atomic spectra, the nature of light and the measurement of spectral Doppler shifts, have given us the models and tools of revolutionary nature to expand our understanding of both the microscopic and the macroscopic universes. Even today, the most precise and delicate measuring tools for the galactic, atomic and nano-particles, are optical or photonic, because photons are mass-less entities of most precise frequencies. Today’s “Global Village” and “Global Economy” are the direct results of fiber optics communication and the internet revolution, all enabled by the photonics industry. The discoveries and inventions during the first part of the twenty-first century will certainly be dominated by the broad enabling power of optics/photonics science and technology. Thus, developing infrastructure for the rapid spread of optics education is of global importance.

1.2 Economic consequences of advancement in science and technology

Knowledge has become the “capital” for today’s science and technology driven global economy. The rate of innovation has become the key metric for global competitiveness. Properly educated knowledge workers can learn to create wealth for themselves even in the poorest countries. Development (i.e., wealth creation) has become synonymous with quality education, and consequent freedom of mind. In the process, the socio-political inter-relations and the governing processes have been undergoing radical changes. The meaning of “management” is changing from “controlling hired hands” to “empowering and inspiring knowledge workers to innovate”. Even paradigms like “demand and supply” and economic theory based on “limited natural resources” are beginning to change to “abundance through technology” ushering in “empowered economy” of “supply for all real needs”, because we now have the knowledge and technology to transform almost any material to any other desired materials. It is only a matter of cost of the energy necessary for this transmutation and transformation. Sustainable knowledge economy now needs universal education, like universal suffrage. Let us do our part to globalize optics/photonics education.

1.3 Knowledge economy demanding faster socio-political changes

Before the invention of paper and then printing machines, preservation of the accuracy (“purity”) of human knowledge was a difficult and delicate endeavour. Privileged class had to evolve to preserve and teach to new generations. Consequently, we evolved into an educational system that is essentially "of the elite, by the elite, and for the elite", out of necessity. Now we have the other extreme: the internet is over-flooded with information or “content”. But, the problem is how to create usable knowledge out of this overflowing information and then how to use the knowledge to create wealth for the well-being of all in society. While the poor of the world are far better off today than any time in the past, the empowering knowledge gap and wealth gap are rising much faster than any time in history.

Without higher education, one cannot participate in today's knowledge economy. In spite of the overflow of free information, higher education is too expensive. Barely 1/3 of the population can afford it even in the most developed countries. Physical infrastructure does not exist to accommodate the other 2/3 of the population. Even if the infrastructure is created, the cost of its use will skyrocket, barring all but a few wealthy elites. Yet, without a much larger number of innovators (through higher education), a country’s industry cannot compete in the global knowledge economy. We must promote the evolution of new, high-quality educational models that can reach out to global billions within their economic reach. Instead of just handing out fish, we need to figure out how to help people learn for themselves “how to catch fish” while, at the same time, nurture the fish habitat for sustainability.

1.4 Mass education needs novel approaches to reach out to a diversity of students

All people are born with some 100 billion neural cells. To sustain the evolution of the specie, different social members are genetically endowed with different modes of creative intelligence and learning skills. However, the current academic evaluation system favors left-brain, analytical and articulate group. This may represent about 15-20% of the population. The other 80-85% of the young children may feel disenfranchised early in their life by being
branded as “slow” by various degrees, especially, when they come from underprivileged families; unfortunately, they are the majority in the global population. We need to develop a system for knowledge creation, organization and delivery that is economically accessible, spiritually enlightening and applicable in the real world to a diversity of students. It must be available to all the people, all the time and all over the world. We need to develop updateable, high-quality, multimedia, and contextual education materials. We need to make the content easily available on the global web and it must be available at low cost. The contents must be customizable to the learning objectives and cognitive styles of the individual learners. We need intelligent software to aid customization.

1.5 Effective teaching of diverse student population is a very complex process

What are the exact cognitive processes and styles of different learners? What are the self-actualizing learning objectives of diverse people in a changing world that is continuously accelerating? What are the types of natural intelligences of people that may help us customize the style of presentation of the educational materials? These are all fuzzy and controversial, soft, social-science issues, yet they are critical in defining long-term educational philosophy.

We propose to make the whole world an experimental school through the use of the Global Internet. Thus, we must consciously facilitate diversity of experiments around the world that intend to meet the various local needs and we should organize ourselves to learn from each others successes, as well as failures, to accelerate our collective progress. We must develop collaborative understanding between all local optics education schools and institutions along with all the global photonics industry clusters. So, let us try to develop a flexible, but a concrete infrastructure that will allow numerous, unbiased experiments, results of which can be freely shared for rapid evolution of all of us.

2. A concrete example: the Global Photonics Education Network (GPEN)

Implementation of the philosophy and solutions proposed in the first part of this paper, require a concerted effort on the global scale. We present here an example of such an effort aimed at the photonics education sector: the Global Photonics Education Network (GPEN).

As part of the Education and Training in Optics and Photonics (ETOP) conference held in Singapore in November 2001, a panel discussion entitled “Global Networking to Promote Local Technician Education – Problems and Solutions” was held. Members from 9 countries exchanged view on the subject and agreed to form a global network to address local issues in photonics education and training. This led to the creation of the GPEN. In what follows, we review what has happened since, and present a plan of what could happen in the future for the GPEN. This draft plan is serving as a start for further discussion on the GPEN and is not intended to be final by any stretch of the imagination. Feedback from current and future “global networking enthusiasts” will shape this plan and enable it to become the blueprint for a more formal and firmly established the GPEN, with a clear direction and mandate [1]. This draft plan has been the object of discussions at the SPIE Annual Meeting in San Diego, CA (3-8 August 2000) and at the ETOP 2005 conference in Tucson, AZ (6-8 October 2003). The interested parties who couldn’t attend those meetings should send their comments and suggestions by email to Drs. Marc Nantel (mnanetl@pro.on.ca) and Chandra Roychoudhuri (Chandra@phys.uconn.edu) for further circulation among the active volunteers.

2.1 ETOP 2001 and the first Panel

At the 2001 ETOP conference, a Roundtable Panel was assembled and organized by Prof. Chandrasekhar Roychoudhuri from the University of Connecticut (USA) and Tuan-Kay Lim from the Nanyang Technological University (Singapore). The Panel generated a report that was published in the ETOP 2001 proceedings [2]. The Panel discussed the following questions, as stated in its abstract:
- “The global Internet system has ushered in the Knowledge Age. Since the core infrastructure of the Internet is based on Fiber optics and semiconductor laser based technologies, the field of optics/photonics now enjoys a privileged position. Thus, Scientific and Technological Education in Photonics (STEP) is critical to enhance and/or maintain economic competitiveness in IT industries.”
- “Expanding and extending educational facilities is an expensive, difficult and slow process even in developed countries.”
- “High School and early college level education in optics/photonics science & technology is critical to the economic well being of the optics and communication industries around the world.”
- “[…] identify the various geographical (local) issues and solutions (actual and potential) that can be emulated globally through various networking possibilities, aided by international optics/photonics societies. We can take lessons from the successful concept of global networking between local optical industry clusters to promote sustainable economic growth.”

Participants included the audience and panel members Chandrasekhar Roychoudhuri (Chair, USA), Bob Breault (USA), Judy Donnelly (USA), Art Guenther (USA), Dan Hull (USA), Roger Lessard (Canada), Marc Nantel (Canada), John Marsh (UK), Pierre Chavel (France), Ari Friberg (Sweden), Valery V. Tuchin (Russia), Ajoy Ghatak (India), Tuan-Kay Lim (Singapore), and John D. Love (Australia).

The panel discussions generated the following recommended actions:
(i) Organize an Optics Global Networking website with SPIE & ICO sponsorship, and with the guidance of this Roundtable members as an Ad-Hoc Committee.
(ii) Get as many societies and industry clusters involved in this global networking as possible.
(iii) Organize regional nodes of this Global Network under the sponsorship of local society chapters and industry clusters.
(iv) Carry out global survey of various needs with the help of clusters and societies. This could lead to the standardization of the core, invariant, scientific portion of the curriculum, while the industry clusters can customize the rapidly changing technology portion locally [2].

Since the first Panel, the first recommendation above has been implemented: a discussion forum was graciously provided by SPIE on their webpage (http://spie.org/app/forums/, and then “Technician Education”) to facilitate exchanges between Global Photonics Education Networking enthusiasts. SPIE also provided the GPEN organizers with a document outlining what would need to do to further the development of the Network. It was agreed with SPIE and the organizers of the ETOP 2003 conference that there would be continuing discussions on the Network at the 2003 SPIE Annual Meeting (San Diego, CA, USA, 3-8 August 2003) and at ETOP 2003 (Tucson, AZ, USA, 6-8 October 2003), where special meetings were held on the subject. This draft plan intended to suggest a possible way to go for the Network, and is the document that was discussed at those two meetings.

2.2 Importance of “clusters”

One recurring theme from the first Roundtable Panel discussion and subsequent exchanges dealt with the crucial role “clusters” could take in the formation and operation of the GPEN. A cluster is a group of local companies, educational institutions and other stakeholders rallying around a particular sector of the economy or industry [3]. By pooling resources, a cluster can network, share best practices, influence local political economics, and lobby provincial, state or federal levels of government. One of the essential aspects of a cluster is that it be local, regrouping members from within, say, a 50-100-km radius. In photonics, the industry clustering efforts are being promoted internationally by Dr. Bob Breault from Breault Research Organization in Arizona (USA). There exists now photonics industry clusters throughout the world [4].

It seems clear that a well organized Global Network in photonics education would be most useful if it can facilitate the access to all the diversity of global best practices to the local educational leaders explicitly interested in strengthening the business base of the local photonics industry clusters. Because of the inherently local nature of industry clusters, the GPEN, by virtue of its vision of providing the global photonics education infrastructure, could be the facilitator to build “cluster of clusters”, or a “super cluster”, to borrow a term from our colleagues in astronomy. The establishment of a local cluster requires some critical mass of industry and academic institutions interested in photonics and the dedication of a few individuals to organized and maintain it. This means that the GPEN should inspire academics and industry engineers and scientists to participate in GPEN activities that promote their local interests through their local or international societies. By promoting excellence in local technical and advanced education, by providing easy access to sharing global best practices, GPEN will naturally facilitate the start and growth of local photonics industry clusters. GPEN can provide useful resources to new and existing local chapters of SPIE, OSA, IEEE, etc., which, in turn, nurture local industry clusters. However, more focused organizations designed specifically to promote local photonics education for the specific purpose of accelerating the growth of local photonics industry, would be an important approach for many countries. A few of the interesting examples include the National Association for Photonics Education and Training (NAPET) in Singapore, the Ontario Photonics Education and Training Association (OPETA) in Canada (ww.opeta.ca), Photonics Valley in Paris, etc. We should note that most of the original participants of the 2001 Roundtable meeting are local education leaders and
are involved in organizing and promoting photonics education in many new ways to reach out beyond the needs of their immediate institutions.

3. GPEN’s organization, and its future growth

The GPEN, right now, is little more than a few people around the world, loosely bound by the spirit of one meeting in 2001, and follow-up meetings in 2002 and 2003, two proceeding papers and a SPIE discussion forum. While this doesn’t look much, the key ingredient is already there: people who care about photonics education and who have a global view of it. Where does one go from there?

3.1 First thing first: communication links

The single most important tool to set up for GPEN is a line of communication between its members and would-be members. The current format of the discussion forum on the SPIE webpage is not sufficient on its own. To add some immediacy to the exchanges, we will implement a four-pronged approach to be implemented in parallel: (i) a webpage, (ii) a web based discussion forum (currently, SPIE is providing), (iii) a list-serv email address, and (iv) regular meetings.

The list-serv is a single email address to which a member from the list sends an email that will reach all the other members of the list. It is the simplest way to reach everybody at the same time. When meetings have to be set, policy has to be discussed, new resources have to be publicized, it is a very useful tool. There is usually a list-serv manager who screens new applicants for relevance (would likely be the Chair of the GPEN). A general etiquette has to be followed when using list-servs to avoid mass mailing intended to only one member, or to avoid spam. There are several commercial but free list-serv providers where all the exchanges are archived and can be accessed only by the members of the list. SPIE, OSA, ICO could also decide to provide this service if it is within their capabilities. The most glaring limitation usually encountered with this mode of communication is a limit on the size of the messages, which greatly reduces the possibility of sending attachments…

…Which is why the list-serv is best used in tandem with a content-based webpage. The webpage would not be use for discussions and on-going exchanges per se, but for posting important resources that are of interest to the GPEN community in general. A look at the OPETA webpage at www.opeta.ca can give an idea of what can be implemented: Mission and Vision statements, news, membership list and links, photonics education resources, forms… If updated regularly, the webpage can be a precious resource for members and non-members alike. This is where one could post a calendar of events (special meetings, conferences, workshops, and call for proposals), recently published photonics education standards, new curriculum and research papers, for example. Web hosting is relatively cheap, and it is best for the global community that it be administered by our international societies (SPIE, OSA, ICO, LIA, IEEE…) with the necessary coordination… The content of the webpage would be provided by members and international societies. A “paid members only” section could be implemented if some of the content has financial value like books, special proceedings, etc.

While distance communication is necessary for any endeavor on the global scale, face-to-face meetings are still the best way of exchanging and networking. Regular meetings could be arranged in cooperation with large international conferences worldwide such as the ETOP, SPIE, OSA, ICO, IEEE-LEOS, etc., and other similar events in Europe, Asia, Oceania and Africa. These could be divided in GPEN general meetings where issues of interest to the whole network would be discussed and decided upon, and GPEN local meetings looking after the more local needs. Minutes and reports of these meetings would be made available to the whole GPEN membership through the list-serv and the webpage. If the means are available, remote participants could join these meetings through teleconferencing, video-teleconferencing or web-teleconferencing, for example.

The current discussion forum on the SPIE webpage can still find a useful place in that format, especially since an increased communication between members through the list-serv will generate discussion threads that will be better expanded upon in the discussion forum (instead of crowding the list-serv with ongoing subject of interest to a specific but limited sub-group of the membership). Each prong of the four-pronged approach presented above should reinforce the others in a similar way, leading to more exchanges between global photonics education enthusiasts.

3.2 The membership

So far, the informal “members” of the GPEN have been the participants to the few past meetings. While it features a good international representation, the GPEN would no doubt have to recruit many more international participants to
be truly representative of the global distribution of photonics education and training. Even though the first meeting, sponsored by ETOP-2001 Conference, focused on education for technicians, the formative spirit of GPEN has been broader – to promote education from grade school to life-long-learning (K-100!), including outreach and continuing education. The participants of the original meeting understood the significance and the importance of this broader vision. It is clear that there are a few groups from which GPEN should recruit:

- **Photonics Education Clusters:** Those include organizations like OPETA in Ontario (Canada), NAPET in Singapore, Project PHOTON in New England (USA) and other groupings whose primary goals involve photonics education and training, at any and all levels. Mostly populated by educational institutions, outreach groups, government bodies and some industry members.

- **Photonics Industry Clusters:** These are local industry associations with the advancement of the photonics industry at heart. They are usually composed of members from industry, government and academia. Examples include OPTIC and OPC in Ontario (Canada), AOIA in Arizona (USA) and the Optics Valley of China (PRC). Others in Europe were mentioned earlier.

- **Professional societies:** There are members from SPIE, OSA, LIA, IEEE, APS and other organizations with a strong interest in photonics education and training. When the GPEN is better established, publicizing its existence to them would be beneficial for recruitment in general and for broadening the reach of the network.

- **Conference participants:** The current “members” of the GPEN mostly involve people who attended ETOP 2001 in Singapore and the follow-up meetings in 2002 and 2003. As regular meetings co-located with major conferences take place, the chance to recruit more global networking enthusiasts will be increased.

### 3.3 Vision and Mission, goals and deliverables

Nothing has been formally laid down for the Vision, Mission, goals and deliverables for the Global Photonics Education Network. Partly, this is because it should be the membership who sets them. First, establish communications links, then populate them with interested parties, set up a loose governance and THEN proceed to lay down the organizational principles on which the GPEN will rest. The Vision and Mission statements, as well as goals and deliverables, are best set by the people who will populate the network, not the few who are keeping it greased and in working order. This still remains to be done by the GPEN membership at the time of this writing, but an example of what could emerge is shown below:

**Vision:** Facilitate the networking between local education promoters and all the available diversity of global best practices. (Just as the name “Global Photonics Education Network (GPEN)” literally implies.) While this vision statement can be improved and/or expanded by all the participating interested parties, the original international meeting at the ETOP-2001 was organized with this spirit of bringing the greater good to all photonics educators, students, and industry worldwide. This vision is also implicitly or explicitly embedded in the missions of almost all the Education Committees of the international societies. This brings the open question: “What should be the specific functional role and mission of GPEN?” Broadly speaking, it should function synergistically with the international professional societies and the photonics industry clusters to facilitate the formation of an effective network of education clusters. This is probably the key new function of GPEN that will synergize the functions of education committees of the international professional societies.

**Mission:** GPEN will achieve its Vision through following its five Mission statements:

(i) Facilitate the development of local photonics education clusters in support of GPEN and of local photonics educators;
(ii). Provide a networking opportunity for photonics educator with their colleagues from around the world;
(iii). Facilitate the free exchange and circulation globally of curriculum ideas, standards, aids and experiments;
(iv). Promote the spread of distance education in photonics (web-based or otherwise) to bring photonics education to all areas of the world, including to those below the critical mass to mount their own programs;
(v). Facilitate the formation of a united voice for the global photonics education community out of the locally diverse needs at different levels.

One can then drill down into the specifics of what the GPEN will want to accomplish and the priorities (both temporal and in importance) that it will set. This is especially true since for each goal/deliverable set there should be
a dedicated sub-group of GPEN volunteers/members making it happen. Again, this is yet to be developed by the membership. Subjects that are likely to find themselves on the list of goals and deliverables include recruitment, internal and external communications, local cluster formation, photonics education and training needs analysis, and educational resources and programs. The list of possibilities is endless, and should reflect the priorities of the GPEN membership and of the individuals willing to push these agenda items to their fruition.

3.4 Governance

An organization like the GPEN would see little progress without some amount of structure in its governance, but too heavy a framework can collapse on itself, until its vision, mission and its services are well articulated. Once the specific nature of the organization is well defined, we will be in a position to emulate the right “Governing Structure” out of a wide variety of successful “non-profit” organizations and their “sub-organizations”.

To accelerate the process of structural maturity, the Ad-Hoc Committee Members (the participants of the last several GPEN meetings) probably should elect an Ad-Hoc Chair and Ad-Hoc Vice-Chair for a definite period of time. During this period, the Chairs would be responsible to lead the development of a permanent organizational structure, based on the consensus recommendation extracted out of the Ad-Hoc Committee Members. The Ad-Hoc Chairs should also be empowered to form Ad-Hoc Sub-Committees to put GPEN in a functionally “running mode”. Gathering this “running mode” experience is critical for our long-term success, as we are embarking on “nebulous”, non-profit activities, which are already part of the desired functions of most of the professional societies. So, finding our functional niece, as a necessary and useful new organization (sub-organization), will be critical during the coming years.

3.5. Budgetary considerations

The costs to make a network like the GPEN happen can start at near zero if all that is wanted is a networking tool, and can climb limitlessly from then on as required by the goals/deliverable sets chosen. The bare minimum to starts the GPEN in a meaningful way is the list-serv (can be free), the webpage (free to the GPEN if provided by a member), the regular meetings at SPIE/OSA/ICO/IEEE-LEOS, etc., meetings (free to the GPEN provided by conference organizers and transportation/accommodation paid by the participants), the consumables (including long-distance telephone conversations, photocopying, faxing, mailing, can be expected as in-kind from members).

4. Conclusion

In this paper, we identify shortcomings of the current higher education paradigm and propose possible solutions. One major problem is that higher education is currently reserved to the few who can afford it, while the vast majority of the population is missing out on fulfilling their intellectual potential. As part of the solution, in particular, we single out the recent globalization phenomenon and the way the internet and optical fibre telecommunications have enabled it. While the current education system has evolved from a time when the transmission of knowledge was difficult and costly (before paper, before printing), thereby limiting it to the well-off, we now live in an era when the World Wide Web makes available most of the knowledge ever generated virtually free of charge. This immense education potential must be tapped. We propose that global networking between educators can serve local education needs around the world through a more egalitarian distribution of knowledge and expertise. As an example, we present the Global Photonics Education Network, which aims to link optics/photonics educators worldwide to make education and training in that subject of a higher quality and more easily available to all parts of the world.

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Abstract: WebTOP is a three-dimensional, interactive computer graphics system developed at Mississippi State University to help students learn about waves and optics. It has been used to help teach undergraduate introductory physics and upper-level optics classes. Currently, it is comprised of sixteen modules spanning eight different subject areas. The subject areas are waves, geometrical optics, reflection and refraction, polarization, interference, diffraction, lasers, and scattering. WebTOP simulations have the following characteristics. First, they are three dimensional, i.e., they have navigation controls that allow the user to rotate the scene, pan, or zoom, in order to view it from any desired orientation. Secondly, they are interactive. The user can change the parameters either by typing in the desired values into the appropriate text entry box, or by using the mouse cursor to move the appropriate widget in the scene. Thirdly, the simulations are animated, for those phenomena for which animation is appropriate. Furthermore, the simulations include VCR-type controls that allow the user to record his/her interactions with the simulation for later retrieval, viewing, and editing. Finally, these modules run inside a web browser. They can be run from our website, http://webtop.msstate.edu, or they can be downloaded from this website and run on the user’s local machine. This paper provides an overview of WebTOP and a description of each of the modules.

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1. Introduction

The Optics Project on the Web (WebTOP) is a Web-based 3D interactive computer graphics system that simulates optical and wave phenomena [1-3]. Its purpose is to help instructors teach and students learn about waves and optics. The current version includes sixteen modules: Waves, Lenses, The Eye, Reflection and Refraction/Vectorial, Reflection and Refraction/Waves Two Media, Reflection and Refraction/Waves Three Media, Polarization, Michelson Interferometer, Fabry-Perot Etalon, Fraunhofer N-Slit, Transmission Grating, Rayleigh Resolution, Fresnel Single Slit, Fresnel Circular, Scattering, and Lasers. Each of the modules includes an interactive simulation, an overview of the relevant theory, a showcase of examples, and a list of suggested exercises.

The WebTOP simulations are implemented using the Virtual Reality Modeling Language (VRML) [4], Java, and the External Authoring Interface [5]. They run in Microsoft’s Internet Explorer Web browser with the Blaxxun Contact 5.0 VRML browser plug-in installed [6]. WebTOP simulations include VCR-type controls that allow users to record their interaction with the simulation in the form of small XML scripts [7]. The scripts are human-readable and can be easily edited. They can be used for viewing a pre-recorded session, setting up example web pages, or for simply initializing modules.

WebTOP is used to help teach both upper-level undergraduate (junior/senior) optics courses and/or the wave and optics parts of introductory physics courses (both calculus-based and algebra-based) in more than a dozen universities. In this paper we first describe the features of a typical module, and then discuss the capabilities of each module. Finally, the use of WebTOP in classroom settings is discussed.

2. Features of a WebTOP module

A typical WebTOP module window is shown in Fig. 1. It has five basic parts: the Scene, the Navigation Icons, the Console, the Recording Panel, and the Activities Menu. Each of these will be described below.

The Scene is the interactive 3D simulation itself and occupies the largest part of the Web page. It usually consists of a light source, a variety of optical elements, and an observation screen. The parameters of these items can be modified either by direct manipulation of the “widgets” in the scene, or by typing the desired parameter values into the appropriate text entry boxes on the Console.
For example, in the Fresnel Single Slit module shown in Fig. 1, the scene consists of a single slit, an observation screen, and three kinds of widgets that allow the user to change the parameters of the simulation. In this module a monochromatic plane wave of wavelength $\lambda$ is normally incident upon a slit of width $w$. The resulting diffraction pattern is observed on an observation screen that is a distance $z$ from the plane that contains the slit. Spinning the Wavelength widget changes the wavelength. Pulling on the Width widget changes the width of the aperture. Pulling on the Screen widget changes $z$.

Fig. 1. The WebTOP window for the Fresnel Single Slit Module. Underlined labels indicate the five basic parts of the window; the other labels point to the widgets used in the module.

The Navigation Icons allow the user to control the appearance of the scene. From left to right in Fig. 1 they are: the Viewpoint icons, the Zoom icon, the Pan icon, the Rotate icon, and the Hide Icons icon. The Viewpoint icons (the Fresnel Single Slit module shown in Fig. 1 has two) return the scene to predefined orientations. The Zoom icon allows the user to zoom into or out of the scene. The Pan icon allows the user to translate the scene left/right or up/down. The Rotate icon allows the user to rotate the scene. The Hide Icons icon allows the user to hide and show all the other navigation icons.

The Console is near the bottom of the window (see Fig. 1). It has three functions. First, it tells the user the current values of the input parameters, and the values of other important quantities. For example, in Fig. 1 the Console is reporting that the values of the input parameters are wavelength = 550 nm, slit width = 0.55 mm, and $z$ = 21.06 mm, and that the value of the Fresnel number is 6.6. The second purpose of the console is to allow users to change the input parameters by typing in the desired values. The third function of the Console is that it provides context sensitive help messages on the use of the widgets, and read-outs from sensors in the scene. For example, if the mouse cursor is placed over the observation screen in Fig. 1, the console reports the corresponding position on the screen and intensity at that point.

The Recording Panel is at the bottom of the window. It contains VCR-like controls that allow the user to record a WebTOP session, store it in the form of a script, and then play the script back at a later time. Scripts can also be used to provide example web pages or to set up the initial parameters for a module. The names of the buttons in the Recording panel are, from left to right: Reset, Record, Play, Pause, Stop, and Open.

There are two modes of operation of the recording feature of WebTOP, the RAM-Mode and the Disk Mode. In the RAM mode, the user can record a session and replay it but cannot save it to disk. The recording is lost when the
user closes the browser. The disk mode allows the user to save the sessions to the computer hard disk and to open and play sessions that are on disk. In order to use the Disk mode you must install the WebTOP recording library on your computer. When placed on a website, WebTOP scripts can be replayed even by users who choose not to install the recording library.

The Activities Menu is at the top of the window. It lists the five activities available in WebTOP: the title of the module (Fresnel Single Slit in this case), Directions, Theory, Examples, and Exercises. It also provides a link to the other modules. The title provides access to the interactive simulation itself. The Directions activity contains documentation on how to interact with that particular module. The Theory section presents an overview of the physics being simulated in the module. The Examples section is a Web page that contains descriptions of and links to previously recorded WebTOP sessions in the form of scripts. The scripts are loaded by clicking on the name of the example, and then played by clicking on the Play button on the Recording Panel. The Exercises section provides exercises for the user to try. These are inquiry-based exercises in that the user is asked to interact with the module, observe how the simulation changes, and then come up with an explanation for what is happening. Clicking on Other Modules displays a list of the other modules that the user can access.

3. The WebTOP modules

In this section we will provide a short description of each of the sixteen WebTOP modules.

The Waves module simulates waves in a ripple tank. The user can place one or more monochromatic point sources and/or monochromatic line sources on the water surface. The module shows the resultant disturbance, either as a still picture or as traveling waves. For each point source the user can interactively vary the amplitude, wavelength, and initial phase of the wave it generates, as well as the position of the source. For each line source the user can vary the amplitude, wavelength, direction of propagation, and initial phase of the wave it generates. In Fig. 2 the Waves module is simulating the interference of the waves from two point sources.

![Fig. 2 The Waves module showing the interference pattern due to two point sources.](image)

Figure 3 illustrates the Lenses module. This module simulates the behavior of light rays as they pass through a system of lenses and stops on an optical bench. The user can choose from amongst several different objects: an on-axis point source, an off-axis point source, a point source at infinity, five point sources in the shape of a T (as in Fig. 3), etc. The user can put an unlimited number of lenses and stops on the bench. The position, diameter and focal length of each lens can be varied interactively, as can the position and diameter of each stop. Each point source on the object emits a large number of rays at random angles, and these rays travel through the system according to the laws of paraxial geometrical optics. A movable observation screen allows the user to see the ray distribution in any plane perpendicular to the axis of the bench.

The Eye module simulates image formation by a human eye with either normal vision or vision that needs corrective lenses. The user controls the position of the object being observed, the length of the eye, and the minimum and maximum focal lengths of the eye. The eye automatically accommodates as the object is moved. In addition, the module allows the user to place a corrective lens (either an eyeglass lens or a contact lens) in front of the eye to see the effect that this has on the image formed. Since the object distance and the eye length scales are
typically quite different, two views are depicted simultaneously: a far away view which shows the object and a small eye, and a close-up view that shows the image on the retina, the corrective lens (if any) and the rays of light entering the corrective lens-eye combination. In Fig. 4 below, an object is outside the far point of a myopic eye, and the resulting image formed by the eye is in front of the retina.

![Image of Lenses module with observation screen positioned in the image plane.](image1)

**Fig. 3** The Lenses module with the observation screen positioned in the image plane.

![Image of Eye module.](image2)

**Fig. 4** The Eye module. The object (yellow arrow) is outside the far point of a myopic eye, and the image (red arrow) formed by the eye is located in front of the retina. The position of the retina is denoted by the white line.

In the Reflection and Refraction/Vectorial module light is incident upon a planar interface that separates two homogeneous media (see Fig. 5 below). The user can choose the incident electric field to be either completely polarized or to be unpolarized. In the completely polarized case, the user can interactively vary the wavelength, the angle of incidence of the incident wave, the amplitudes of the two components and the phase difference between them. The corresponding time-varying incident, reflected, and transmitted (refracted) electric field vectors along the corresponding ray paths are displayed on the screen. The user can select which components of the electric field are displayed.

The Reflection and Refraction/Waves Two Media module simulates a monochromatic plane wave of s-polarized light incident upon a planar interface that separates two homogeneous media (see Fig. 6). Instead of displaying the relevant electric field vectors, as is done in the Reflection and Refraction/Vectorial module, the wave functions for the electric fields on both sides of the interface are depicted as waves in a ripple tank. On one side of the “borderline” between the two media, the user can display either the incident wave, the reflected wave, or the
superposition of the two. On the side of the borderline, the transmitted wave is displayed. The user controls the wavelength, amplitude, and angle of incidence of the incident wave, and the indices of refraction of the two media.

Fig. 5 The Reflection and Refraction/Vectorial module. Circularly polarized light is incident from air onto glass at Brewster’s angle.

Fig. 6 The Reflection and Refraction/Two Media module. S-polarized light is incident from glass (on the left) onto air at an angle of incidence greater than the critical angle.

The Reflection and Refraction/Waves Three Media module (see Fig. 7) is an extension of the Waves Two Media module. It simulates a monochromatic plane wave of s-polarized light as it travels through three different homogeneous media. The wave functions for the electric fields in each of the media are depicted as waves in a ripple tank. The user controls the wavelength, amplitude, and angle of incidence of the incident wave, the indices of refraction of each of the three media, and the thickness of the second medium.

The Polarization module (see Fig. 8) simulates the propagation of the electric field vectors of either a completely polarized or unpolarized plane wave of light and the effects of various optical elements (linear polarizers and wave plates) on the corresponding electric field vectors. The user controls the properties of the incident field, and the type, location, and characteristics of the optical elements being used. For a linear polarizer the user can vary its position and the angle that its transmission axis (TA) makes with the positive x-axis. For a wave plate the user can vary its position, the angle that its fast axis makes with the positive x-axis, and its thickness in units of the incident wavelength.
In the Michelson Interferometer module light from a monochromatic point source is incident upon a Michelson interferometer (see Fig. 9). The resultant intensity pattern is displayed on an observation screen, and a graph of the intensity as a function of position across the center of the pattern is displayed above the observation screen. The user can vary the wavelength of the incident light, the rotation angle of the tilt mirror, and the position of the translation mirror.

In the Fabry-Perot Etalon module light from a monochromatic point source is incident upon a dielectric slab whose surfaces are coated with a reflective coating (see Fig. 9). The resultant interference pattern is displayed on an observation screen, and a graph of the intensity as a function of position across the center of the pattern is displayed above the observation screen. The user can vary the wavelength of the incident light, the reflectivity of the faces of the slab, the thickness of the slab, and the index of refraction of the slab.

The Fraunhofer N-Slit module simulates a plane wave of monochromatic light of wavelength $\lambda$ that is normally incident upon a plane that contains $N$ identical slits ($N \geq 1$). The resulting intensity pattern is displayed on an observation screen, and a graph of the intensity as a function of position across the screen is displayed above the observation screen (see Fig. 10). The user can vary the wavelength of the incident light, the number of slits, the slit width, the distance between consecutive slits, and the distance from the slit plane to the observation plane. Moving the cursor over the screen causes the intensity at that point to be displayed on the console.
In the Transmission Grating module a polychromatic plane wave is incident upon a transmission diffraction grating, and the resulting intensity pattern is displayed on a semicircular observation screen (see Fig. 10). The user can select the spectrum of the incident light to be that of a pre-defined standard gas discharge tube (hydrogen, helium, sodium, or mercury), or can create a “user defined” spectrum by entering various wavelengths. The mouse cursor acts as a sensor and, when placed over the observation screen, allows the user to read the angular position of the cursor (and hence the position of the various diffracted orders on the screen).

In the Rayleigh Resolution module monochromatic light from two distant point sources separated by a small angle is incident upon a lens (see Fig. 11). The resulting intensity pattern is viewed on an observation screen positioned in the focal plane of the lens, and a graph of the intensity as a function of position across the center of the pattern is displayed above the observation screen. The user can vary the wavelength $\lambda$ of the light, the angle $\theta$ between the sources, and the diameter $D$ of the lens. The Console displays, in addition to the values of $\lambda$, $D$, and $\theta$, the value of the minimum angular separation for which the two images can be resolved (according to the Rayleigh resolution criterion).

In the Fresnel Single Slit module a monochromatic plane wave of light is normally incident upon a single slit (see Fig. 11). The resulting diffraction pattern is observed on an observation screen, and a graph of the intensity as a function of position across the screen is displayed above the observation screen. The user can vary the wavelength of the light, the width of the slit, and the distance from the slit to the observation screen. The parameter ranges are such that the user can explore the Fresnel region, and the beginning of the Fraunhofer region. Moving the cursor over the screen causes the intensity at that point to be displayed on the console.
In the Fresnel Circular module a monochromatic plane wave of light is normally incident upon either a circular aperture or a circular obstacle (see Fig. 12). The resulting diffraction pattern is observed on an observation screen, and a graph of the intensity as a function of position across the screen is displayed above the observation screen. The user can vary the wavelength of the light, the diameter of the aperture or obstacle, and the distance from it to the observation screen. Moving the cursor over the screen causes the intensity at that point to be displayed on the console. The parameter ranges are such that the user can explore the Fresnel region, and the beginning of the Fraunhofer region.

The Scattering module simulates the non-resonant scattering of light from an atom (see Fig. 13). The atom is located at the origin, and the incident light is traveling along the negative y-axis in the positive y-direction. An oscillating vector depicts the induced dipole moment of the atom. Scattered electric field vectors are depicted at sets of observation points along three different axes: the positive x-axis, the positive z-axis, and a movable axis whose angular position can be varied by the user. The user can choose the incident electric field to be either linearly polarized or unpolarized. When the incident light is linearly polarized, the user can change the amplitudes of the two components of the electric field vector and the wavelength of the light.

The Lasers module simulates the behavior of an optical resonator oscillating in one of the following four transverse modes (the user selects which one): TEM$_{00}$, TEM$_{10}$, TEM$_{01}$, or TEM$_{11}$. The scene consists of a cavity that has a spherical mirror on each end. The resulting intensity pattern is displayed on an observation screen, and a graph of the intensity as a function of position across the center of the pattern is displayed above the observation screen.
The user can vary the wavelength of the light, the radius of curvature of each of the mirrors, the length of the cavity, and the position of the observation screen. In Fig. 14 the Lasers module is simulating the TEM$_{00}$ laser mode.

4. Using WebTOP for teaching and learning

WebTOP can be used to help teach an optics course or the waves and optics portion of an introductory physics course, and it can be used by faculty and students in a variety of ways.

It can be used for in-class demonstrations. Its three-dimensional nature allows the presenter to show the phenomenon from the most advantageous viewpoint. The ability to change the values of all the relevant parameters in a simulation allows the instructor to show, in real time, the effect of changing each parameter in a way that can be seen clearly by the students, even in large lecture halls. More importantly, using WebTOP to present material lends itself to “What will happen if …” kinds of questions, providing an ideal mechanism for creating an active learning environment [8].

Furthermore, WebTOP can be used for homework assignments. Students can be asked to complete homework sets in which they are asked to produce numerical or qualitative answers to questions, and then use WebTOP to simulate the situation and check their answers. The students turn in their written answers to the questions and the corresponding screen captures from the relevant WebTOP module.

WebTOP can also be used to supplement laboratory activities. It can be used in pre-lab activities to help explain the phenomenon that is going to be investigated in the lab, or it can be used during the lab to compare actual data to
the simulation results and to help draw inferences when equipment limitations occur. Finally, WebTOP can be used for student projects. Students can work in teams or individually on particular problems and use WebTOP to help illustrate their presentations and reports.

At Mississippi State University, WebTOP has been used to help teach upper level undergraduate optics courses, a graduate level lasers course, and the waves and optics part of two types of introductory physics classes: calculus-based and algebra-based. It has been used in the introductory courses almost every semester for the past three years, and student evaluations of WebTOP have been performed in every class in which it has been used. The student response to WebTOP has been very positive. In response to the question “How useful did you find the WebTOP demonstrations during class for the visualization and understanding of the optical phenomena in this course?” the 335 students surveyed rated WebTOP 4.53 on a scale of 5. In response to the question “How useful did you find the WebTOP homework during class for the visualization and understanding of the optical phenomena in this course?” the 335 students surveyed rated WebTOP 4.27 on a scale of 5.

5. Conclusion

In teaching and learning optics, we often deal with content that is difficult to understand without good visualizations. WebTOP provides a means to easily visualize phenomena in 3D, allowing users to both look at phenomena from different angles and answer “what if” type questions. WebTOP has been shown to be an effective tool for classroom demonstrations and for homework assignments. It can also be used to help supplement laboratory activities and for student projects. However, WebTOP is not a finished product. We have plans to develop more curriculum material based on WebTOP modules and to develop more modules. We also plan to make WebTOP open source. This will enable users to modify and expand WebTOP, and to adapt its techniques to their particular projects. For more details about WebTOP’s progress visit its website at: http://webtop.msstate.edu.

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6. References


Curriculum in biomedical optics and laser-tissue interactions

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Abstract: A graduate student level curriculum has been developed for teaching the basic principles of how lasers and light interact with biological tissues and materials. The field of Photomedicine can be divided into two topic areas: (1) where tissue affects photons, used for diagnostic sensing, imaging, and spectroscopy of tissues and biomaterials, and (2) where photons affect tissue, used for surgical and therapeutic cutting, dissecting, machining, processing, coagulating, welding, and oxidizing tissues and biomaterials. The courses teach basic principles of tissue optical properties and light transport in tissues, and interaction of lasers and conventional light sources with tissues via photochemical, photothermal and photomechanical mechanisms. More information can be found at http://www.bme.ogi.edu/biomedicaloptics/.

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1. Introduction

The uses of lasers and light in medicine and biology are undergoing an explosive growth. The availability of optical fibers, diode and solid-state lasers, superluminescent diodes, CCD cameras, and new photonic detectors has spurred interest in new applications and development of theoretical understanding of how photons move through and interact with tissues and biomaterials. Today, a body of techniques and associated theoretical modeling is available for engineering design and experimental work.

The curriculum consists of

Biomedical Optics 1: Tissue Optics
Biomedical Optics 2: Laser-Tissue Interactions
Biomedical Optics 3: Engineering Design
Computational approaches to light transport in biological tissues
Computational approaches to laser interaction with biological tissues
Physical and Geometrical Optics
Optical Non-destructive Evaluation
2. Tissue Optics

The course introduces the origins of tissue optical properties, i.e. absorption, scattering, and refractive index. The time-resolved transport of photons is introduced using Monte Carlo simulations to illustrate behavior and diffusion theory to summarize photon transport. Monte Carlo simulations mimic the movement of individual photons through a light-scattering tissue. The Fourier transform of the time-resolved computations yields the frequency-domain descriptions that describe the transport of light from sources modulated at various frequencies. The temporal integration of the time-resolved transport yields the steady-state solutions, the most commonly used form of optical measurement. Hence, the relationship between the time-resolved, the frequency-domain, and the steady-state solutions are illustrated by both Monte Carlo simulations and by diffusion theory. An introduction to spectroscopy and imaging is presented illustrating the uses of tissue optics.

The basics of laser safety are taught before the students are allowed into the laboratory. The key issue is eye safety, with consideration of skin exposures as well. The course includes a laboratory in which the students assemble optical and laser experiments to demonstrate the principles learned in classes.

The introductory course is Biomedical Optics I: Tissue Optics. The follow-up course is Computational approaches to light transport in biological tissues which introduces time-resolved finite-difference modeling and considers Monte Carlo simulations in more detail. Boundary conditions (such as an air-tissue surface or a glass-tissue interface) are considered. Tissue heterogeneities (such as blood vessels or tumors) are considered by the introduction of perturbation theory.

3. Laser-Tissue Interactions

The course introduces the interaction of lasers and conventional light sources with tissues and biomaterials. The topics are photochemical mechanisms of interaction, and examples include photodynamic therapy (a light-activated chemotherapy for cancer and other pathology) and light-activated adhesives; photothermal mechanisms of interactions, and examples include photoablation, hyperthermia, laser welding of tissues; photomechanical mechanisms of interactions, and examples include tissue cutting, vaporization, cavitation, spallation and evaporative dessication of tissues. The course makes use of optical and thermal diffusion theory and the Arrhenius formulation for thermal damage.

The introductory course is Biomedical Optics II: Laser-Tissue Interactions. The follow-up course is Computational approaches to laser interaction with biological tissues which introduces the use of compartmental modeling of coupled differential equations to model photochemical processes, and time-resolved finite-difference modeling to model thermal and ablative processes.

4. Engineering Design

This course is an especially popular offering. The students are asked to organize themselves into a group with a CEO, a chief financial officer, a science officer, a marketing officer, a manufacturing officer, and a regulations/safety officer. This group will develop a business plan for a particular product. The group interviews guest experts (eg., a physician in some specialty), develops a product within a particular topic area (eg., photochemical effects), conducts a demonstration experiment in the lab, prepares a business plan, and presents the plan to an audience of venture capitalists (portrayed by the faculty). The project requires the students to understand the basic mechanism of interaction, be aware of the field of medical practice, utilize their engineering skills acquired in previous classes, and consider other aspects of a project such as ease of manufacture, customer interest in the product, and safety issues. In the past, the students have organized one project every two weeks for a total of five projects that were defended. In this way, the students could play different roles. Although they have successfully done this, it might be better to have only 3 projects and let the students work 3 weeks on each project.

5. Physical and Geometrical Optics

The course introduces first-order Gaussian optics and thin-lens system layout. Photometric theory is applied to
optical systems. The eye, magnifier, microscope, matrix optics, nature of Seidel aberrations are considered. Scalar
diffraction theory; Fresnel and Fraunhofer diffraction are presented. Interferometry is introduced.

6. Optical Non-Destructive Testing

This course is meant to be a graduate level course aimed at introducing the field of optical NDE to engineering
students. The course focuses primarily on coherent light techniques such as interferometry, holography, and laser
speckle methods. Morié, photo-elastic, and structured light methods are also discussed. Specific applications to
biomedical engineering, semiconductor, and electronic materials are presented
Educational and Training program of THz Science and Technology at Rensselaer

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Abstract: Rensselaer is establishing an educational program, THz Science and Technology, with an interdisciplinary faculty team from Departments of Physics, Biology, and Electrical, Computer, and Systems Engineering. Doctoral level students are trained in THz electronics, THz spectroscopy, THz imaging, and THz data transfer and networking. We present examples of focus research and studio based education.

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1. Introduction
In July 2002, Rensselaer Polytechnic Institute established the Center for Terahertz Research. The Center is initiating an integrated education and training program on THz Science and Technology with a team-based, highly interactive, and hands-on studio-based approach.

Under the Rensselaer Plan, adopted in 2000, Rensselaer has chosen to focus investment and resources in information science and biotechnology. Systems or devices that operate in the THz regime are expected to revolutionize both. Proposed novel devices, such as THz plasma wave electronics, molecular spintronics, THz modulators, and photonic bandgap switches will transform future computing, networking, and communication systems. At the same time, THz systems will provide unique opportunities for biomedical imaging, including 3D tomography.

Rensselaer’s THz research program is interdisciplinary, spanning physics, electrical engineering, computer science, biology, and other departments. The research cuts across major centers on campus, including the Center for THz Research, the Center for Broadband Data Transport, the Center for Advanced Interconnect Systems Technologies, and the Nanotechnology Center. Rensselaer is strongly committed to THz research and has provided more than 5,000 square feet of laboratory space for centralized THz research and education, equipped with the help of a $1 million grant from the Keck Foundation.

Rensselaer plans to offer specialized THz courses, for example, THz wave science and technology in imaging/spectroscopy and THz device technology, which will be created and taught in an interactive studio setting by interdisciplinary faculty teams. Besides these studio courses, there will be industrial and international internship opportunities. There will also be special programs in leadership, ethics, life skills, global citizenship, and outreach.

The strength of Rensselaer’s THz program offers an exciting opportunity to create a new model for interdisciplinary, doctoral-level graduate education that offers students both broad exposure and in depth training.

2. Core Physicists in the Center for THz Research and its Near Term Research Focus
THz research at Rensselaer Polytechnic Institute started in the Department of Physics, Applied Physics and Astronomy. Since the first hiring of a THz faculty member (Prof. X.-C. Zhang) from Columbia University in 1992, the department has recruited two more faculty members (Prof. R. Kersting and Prof. I. Wilke) in THz field. In the Rensselaer Performance Plan, the School of Science will hire three additional faculty members in the next four years. These faculty members create the critical mass for THz research at Rensselaer.

During the last several years, scientists and engineers from more than 75 universities, companies, and clinics have visited Rensselaer. Rensselaer’s THz Group has helped scientists from 18 countries learn to use THz sensors in their respective fields. Based on research and education needs, Rensselaer President Dr. Shirley Jackson approved the formation of the THz Center. The Center for THz Research at Rensselaer consisting of four core faculty members was officially announced by the School of Science Dean Joseph Flaherty on July 3, 2002. Two days later, the Institute received word that the W. M. Keck Foundation has awarded Rensselaer $1 million to establish the W. M. Keck Laboratory for Terahertz Science within the new research center. The promise of terahertz wave radiation, known as “T-rays”, is being realized through ongoing research at the THz Center’s state-of-the-art laboratories: Dr.
Xi-Cheng Zhang’s THz Imaging Lab, Dr. Michael Shu’s THz Electronics Lab, Dr. Roland Kersting’s THz Quantum Optics Lab, and Dr. Ingrid Wilke’s THz Spectroscopic Lab.

The Center’s Focused Topics: As a focused research team, the Center will concentrate on five topics in the near future:

**THz Spectroscopy and Imaging**: A team works on the study of protein interactions on surfaces, and protein/protein interactions using THz waves. Based on the fingerprints of acquired spectroscopic information, the team will focus on THz wave imaging, especially on functional imaging for biomedical applications.

**THz Wave Microscope**: A team will develop a THz wave microscope to perform THz microspectroscopy for biomedical sensing and imaging at the cellular level. Specifically, the team will demonstrate an electro-optic THz wave microscope (patent pending) with a spatial resolution of $1/10\lambda$ (wavelength). This non-contact and non-destructive imaging technique maintains the unique feature of providing spectroscopic information in a frequency range from 0.1 to 10 THz.

**Plasma Wave Electronics for Terahertz Emission and Detection**: A team will fabricate new nonlinear plasma wave electronic devices, and achieve efficient and intense terahertz emissions from solid-state devices with two-dimensional electron gas. This project includes the design and fabrication of high mobility heterostructure field-effect transistors, capable of resonant terahertz emission and suitable for the generation of terahertz at higher harmonics, as well as new detector, for GaN-based samples, with a much higher two-dimensional electron gas density.

**THz Biochip Sensor**: A team will develop biochip technology for the detection of monomolecular layers and ultra low concentrations of biomolecules. One of the approaches to biochip technology will be based on metallic grating couplers. Due to plasmon surface resonance, these gratings will increase the interaction between molecular layers on its surface and the terahertz wave by several orders of magnitude. The enhanced sensitivity is expected to allow sensing and fingerprinting of monomolecular layers. THz biosensors will allow non-invasive biomonitoting and control.

**Mathematical Modeling and Computer Science Infrastructure**: To fully develop the applications of THz spectroscopy, T-ray microscope, and biochip sensors, the Center will require a sophisticated mathematical and computer science infrastructure. The process of generating and detecting the THz waves generates massive spectroscopic data sets. Mathematical modeling techniques such as inverse problems, functional data analysis, data mining, and machine learning are at the heart of this knowledge extraction problem.

3. **Major THz Research Efforts at Rensselaer**

THz research is currently conducted at Rensselaer in three major areas: electronics, data transfer and networking systems, and spectroscopy and imaging, as shown in Figure 1.

3A. **THz Electronics**

The upper frequency limit of transistors operating in conventional regimes is limited by the transit time of carriers under the gate for a field effect transistor (FET) or across the base and collector depletion region (bipolar junction transistor). The scaling of feature size has pushed device parameters to the point that transistor operation at a few hundred GHz is feasible. However, device feature sizes have now approached values at which fundamental physics limitations lead to diminishing returns on any further investment in scaling, and alternative device concepts have been proposed. Here, we describe several concepts that are being explored at Rensselaer.
**THz plasma wave electronic devices** THz plasma-wave electronics rely on the excitation of plasma waves in the electronic fluid in high electron mobility transistor (HEMT) channels for the resonant tunable detection and excitation of THz radiation [1]. The waves propagating in this 2D-electron fluid are plasma waves, and their dispersion law is similar to that for shallow water waves (or sound waves), shown in Figure 2(a). This analogy has profound consequences for understanding the physics of 2D electrons in the Ballistic FET. Recently, we demonstrated operation of discrete THz resonant HEMT detectors at 2.5 THz and 600 GHz [2]. We will continue this effort to develop THz plasma-wave electronic technology. Specifically, we will develop THz plasma-wave electronics detector technology that uses arrays of sub-micron FETs.

**Molecular spintronics** Another approach to terascale electronics is to create devices down to nanoscale dimensions. Our particular interest is in the area of molecular electronics. The controlled transport of electrons/holes through a single molecule attached to electrodes forms the basis of molecular electronics. While the idea of utilizing electron spin in addition to charge to control electrical conduction in electronic circuits (spintronics) [3, 4] was discovered some time ago, almost all experiments and theory on molecular wires [5-12] have thus far considered only the charge of conduction electrons (Figure 2(b)). Spintronics devices are attractive for many applications ranging from memory storage and magnetic sensors to quantum computing devices in which electron spins would represent a quantum bit of information.

### 3B. THz Spectroscopy and Imaging

THz electromagnetic radiation between the infrared and microwave bands is often referred to as the "terahertz gap". Compared to medical applications in the microwave, optical and x-ray frequencies, THz radiation methods are not well developed [13]. Perhaps the greatest potential for THz spectroscopy lies in biomedicine [14]. In many cases, THz radiation can potentially create sharper, safer, more informative images at a lower cost than conventional X-rays. THz radiation can provide spectroscopic information about the chemical composition as well as the shape and location of the targets it passes through or scatters from. THz rays are non-ionizing, which means they are non-carcinogenic, and they do not need heavy lead shielding. They can be focused, creating much sharper pictures. These unique characteristics of THz sensing and imaging technologies may improve the accuracy and reliability of cancer detection. Figure 3 shows such an example recently achieved.

Fig. 3. THz imaging of a phantom tumor, including the spectroscopic information.
THz tomography, including computed tomography (THz CT), diffractive tomography, and tomography with binary lenses, is a new tomographic imaging modality that allows pulsed terahertz radiation to probe the dielectric properties of three-dimensional (3D) structures [15]. It provides sectional images of objects in an analogous manner to conventional computed tomography techniques such as X-ray CT. THz CT systems directly measure the transmitted amplitude and phase of broadband THz pulses at multiple projection angles. This allows a wealth of information to be extracted from the target object, including both its 3D structure and its frequency-dependent far-infrared optical properties. Our current research includes: a) Long distance/large target THz imaging, b) Reconstruction algorithms for THz tomography, c) 3D identification of materials, and d) Fresnel binary lens for THz imaging [16-18].

3C. THz Data Transfer and Networking Systems

The need for ever-larger information technology systems is being driven by massive growth in Internet traffic, ever-increasing repositories of information and electronic services, and new computationally intensive challenges at a pace greatly outpacing Moore’s law. Currently, we are addressing basic research issues in THz and electrical data transport, switching, and processing that enable the massive scaling required by these systems. These research challenges span materials, devices, systems, and architecture technologies and will require truly interdisciplinary research. Here we describe selective projects in this research area.

**Terahertz photonics** Terahertz photonics addresses signal processing at THz frequencies. The concept is to use few-cycle THz pulses as information units (bits). While electronic resonances limit the speed of conventional electronics (Figure 4), THz photonics can overcome this barrier and allow signal processing at THz speeds. Of further advantage is the fact that THz pulses can propagate on metallic transmission lines, which allows hybrid-free on-chip integration. The most important future application area for THz photonics is ultrafast data communications, where THz photonic devices may bridge the gap between the speed of fibers and complementary metal oxide semiconductor (CMOS) technology. Recently, we have demonstrated a THz modulator device that makes use of intersubband excitation dynamics [19, 20]. Future research will address the main challenges for the development of photonic THz logics.

![Fig. 4. Electronic resonances of semiconductors set a final barrier to all improvements of conventional devices. The resonances divide the electromagnetic spectrum into two regions. In the low-frequency region information processing can be performed conventionally by charge transport. In the high-frequency region, photonic concepts have to be applied.](image)
**Off-chip optical communications**  As computer data rates become larger and wider, it becomes increasingly difficult to support these bandwidths across MCM (multichip module) dimensions. Tightly integrated MCM/Optoelectronic transceivers that support high bandwidth transmission across larger distances offer a solution. In this project, we will develop materials and waveguide designs that support off-chip optical communications on a ceramic MCM. Project focus areas include waveguides on MCMs (process compatible) and chip-to-waveguide interfaces (including optical vias). We are also exploring the use of novel 3D photonic bandgap structures for possible loss-less switches and guides in photonic systems. An example is shown in Fig. 5. It is created by a single deposition step that uses an oblique angle deposition technique [21-26]. This structure cannot be fabricated using conventional lithographic techniques.

**Broadband networking systems**  The tremendous explosion of bandwidth in the core of the Internet has generally stopped short of end-users due to the well-known “last-mile” problem: The economic infeasibility of installing high bandwidth conduits to homes and businesses. “Fiberless” or Free Space Optical (FSO) networks [27-29] can effectively complement unlicensed-spectrum RF-based wireless local area networks (WLAN) technologies [30-32] to resolve this problem. Although optical networking has become popular in the wired networking world, free space optics (FSO) is still a niche technology used to provide only selected point-to-point links. Several fundamental aspects of free space terrestrial optical communication are yet to be explored. Using trans-receiver pairs that achieve 100 Mbps with 1-10 mW power, we propose dense integration of thousands of trans-receivers into 2-dimensional and 3-dimensional spatial structures. The 2-d array would provide extremely high aggregate bandwidth (100 Gbps and more) over 1-2 km. The 3-d spherical structures (optical antennas) would be combined with LOS auto-discovery and LOS auto-tracking techniques to instantly discover and track LOS if it exists. This work is being performed in collaboration with networking entrepreneurs such as Martin Schoffstall to conduct field trials of a mix of our prototype low-cost FSO-based systems, off-the-shelf 802.11x (wireless international standards) systems, IP routing, and 802.1d bridging protocols.

4. **Detection of Defects in Space Shuttle Foam with THz Imaging Technology**

In this section, we present a recent example of detecting large size defects using THz imaging. Since April 4, 2003, we have been working with Lockheed Martin and NASA Langley Research Center to apply terahertz wave tomographic imaging technology for detecting defects in space shuttle insulating foam samples. Four samples with fabricated defects have been tested. All defects were successfully detected in the small foam samples. In the large foam samples, as shown in Figure 6, Terahertz (THz) imaging identified 49 out of 57 fabricated defects in a Protuberance Air Load (PAL) Ramp Panel with an area of 2 feet by 2 feet and a thickness ranging from 2 to 9 inches.
T-ray imaging has been selected by NASA as one of four potential modalities to detect defects in foam insulation. The four modalities include: T-ray imaging, back-scattered X-ray imaging, microwave imaging and laser shearography. Rensselaer research team believes that this is a perfect research and education opportunity to apply THz wave sensing and imaging technology for real-world application. Figures 7 and 8 show Rensselaer’s research team with Dr. Eric Madaras (NASA Langley Research Center), and two graduate students (Ms. Hua Zhong and Mr. Xu Xie) performing measurement.

The Sprayed-On Foam Insulation (SOFI) used to coat the shuttle fuel tank has low attenuation below 1 THz. This allows T-rays to penetrate through several inches of foam to identify defects buried inside. Compared to conventional technologies, which provide only intensity information of different pixels, T-ray time-domain imaging records an entire waveform of a THz pulse for each pixel. As a result, T-ray imaging provides multidimensional information of scanned objects. For example, when reflected THz pulses are recorded from layers, T-ray imaging visualizes the defects located in the different layers (Figure 9).

The Pal Ramp Panel sample (Figure 6) has three stringers and two flanges at its aluminum base. A layer of conethane separates the two foam layers that have been sprayed on the base. This sample includes two types of defects which may potentially occur in the foam on the fuel tank: voids (or air bubbles) and debonds (or delams), which are separations between layers of foam or between a foam layer and the aluminum base, and range from one-quarter-inch to two inches. The defects were placed as deep as nine inches and as shallow as a quarter-inch from the top of the sample. The defects are not only located at the aluminum base and inner layers of the foam, but also at the
bottom or side of the stringers and flanges. T-ray imaging located 49 of 57 defects, imaging from top and side views. The T-rays were unable to reach three defects.

The T-ray imaging system was set up to scan samples from the top side of the sample. THz radiation is generated from a large aperture GaAs antenna illuminated by a femtosecond laser, and then focused onto the sample using a four-inch focal length parabolic mirror. The THz radiation reflected by a sample is collected by a mirror beside the parabolic mirror, and then focused onto the detection crystal by another parabolic mirror. The THz waveform is then recorded using a $<110>$ ZnTe crystal.

When a THz pulse passes through a defect (either a void or a big gap debond), the timing and amplitude of its waveform may be modulated because the THz pulse passes through less foam at the defect point than at its neighboring normal area. In this case, comparing the peak timing and amplitude of the THz pulse for different pixels identifies the defect. When the THz waveforms are reflected and recorded from the foam layers, the defects located at various depths may be recorded.

Since the foam and base are not uniform for the entire sample, the variation of peak timing and amplitude of THz pulse along the entire foam sample may be even larger than the difference between the defect and its neighboring area. As a result, the defects will be buried in the larger background variation. To solve this problem, a median filter is applied to the image and subtracted from the original to single out the abnormal point.

Certain defects, such as small gap debonds (which do not cause a sufficient change of timing and amplitude of the THz pulse to provide image contrast), may generate a THz temporal waveform distortion. To emphasize the waveform distortion, we calculate the standard deviation or cross correlation of the THz waveform at each pixel with a standard waveform. In the cross correlation or standard deviation map, the defects are clearly defined among the regular points.

Figures 10(a) and 4(b) map detected sample foam defects (near the substrate and near the center layer of the foam). There are a total of 57 manufactured sample foam defects, including 25 voids and 32 debonds. Compared to the debonds, the voids show higher contrast in the THz image. T-rays can visualize all 25 voids measuring 1.5 to 0.25 inches. T-rays were able to detect 24 of the 32 debonds; three were not be reached by the THz waves. Debonds larger than one inch clearly appear in the THz image, and those measuring less than 0.5 inch are difficult to detect.
Circles locate the defects' location

Fig. 10. T-ray image of defects in sample foam. (a) Images of defects created by using a THz pulse reflected from the base. (b) Images of defects created by using a THz pulse reflected from the inner layer. The defect spots are indicated on the construction map of the Pal Ramp Panel in Fig. 6.

5. **Studio-Based Education and Soft Skills Training**

In addition to the strong commitment to research, there is an equal dedication to education, including an expanded and enhanced doctoral program. Rensselaer has won numerous awards for its revolutionary studio-based approach to undergraduate education, including the first Pew Charitable Trust Award for the Renewal of Undergraduate Education and the first Boeing Outstanding Educator Award. The Institute is now adapting and extending the pedagogical principles successfully implemented under this program to doctoral education for students working at the leading edge of science and technology. The goal is to implement an integrated studio program that will enhance the depth and breadth of our students’ understanding while at the same time equipping them with the tools that will be needed for successful careers. Figure 11 shows typical faculty and student interactions in a technology-enriched learning environment.

Fig. 11. Studio based education and soft skills training at Rensselaer Polytechnic Institute.

The IGERT project will integrate our programs in THz materials, devices, radiation, imaging, spectroscopy and computer algorithms to create an environment in which students learn from each other, from on-campus researchers, and from our industrial partners while forming a global network of collaborators and contacts. The curriculum will be highly interdisciplinary. PhD students in THz science and technology will need fundamentals, breadth, depth, and
experimental research experience in a wide range of subjects, including quantum mechanics, non-linear optics, chemistry, materials, devices, optoelectronics, networking systems, and wireless communication. Rensselaer’s strength in these multiple fields provides a unique opportunity to develop a crosscutting interdisciplinary graduate program in the studio mode. Students will build THz-related research skills by choosing fundamental courses in optics and THz science and technology, as well as optional courses in related fields designed to bring breadth to the curriculum. In addition, there will be short courses and seminars delivered by faculty members and by U.S. and International collaborators in the THz research program.

In addition to an innovative curriculum, we will create an infrastructure that nurtures organization, teamwork, communication, mentoring, leadership, and ethics in our students. The IGERT students are required to attend workshops designed by the Rensselaer Archer Center for Student Leadership Development team. This one credit "Professional Development" and "Life Skills" series requires students to be exposed to specific leadership theories and skills, including ethical decision making, developing vision, motivation techniques, communications, teamwork, multiculturalism, and tools to succeed in a diverse organizational culture.

As part of our effort to foster diversity, we will develop a close working relationship with historically black universities and colleges (HBCU). For example, in order to initiate research, HBCU faculty will collaborate with the Rensselaer THz program. A pipeline will allow HBCU students to conduct research at Rensselaer as well as at their home campus and will encourage them to consider the doctoral program in THz science and technology upon graduation.

5. Conclusion

Since 1992, Rensselaer’s terahertz research team members have received grants from both government agencies, private foundations and industries. Examples are the National Science Foundation, Army Research Office, Army Research Laboratory, Air Force Office of Scientific Research, Department of Energy, Defense Advanced Research Projects Agency, W.M. Keck Foundation, Research Corporation, IMRA America Incorporated, Molecular OptoElectronic Corporation, 3D Digital Corp., and Zomega Technology Corporation.

Using these grants, the terahertz center’s labs are equipped with the most advanced photonic and opto-electronic instrumentation for generating, measuring and recording picosecond and femtosecond terahertz radiation waves. The Center will take the lead to use these labs and facilities to create studio-based new courses in major THz research areas for students. Rensselaer’s Center for Terahertz Research stands at the forefront of terahertz technology, we expect THz science and technology to become one of the most promising research areas for transformational imaging in the 21st century, and we educate and train first rate scientists for this challenging transformation.

6. Acknowledgement

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References

Fractional order Fourier transform as a tool for analyzing multi-element optical system

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Abstract: The ABCD matrix formalism, the Collins formula and the complex amplitude distributions on two spherical surfaces of given curvature and spacing are adapted to the mathematical expression of fractional order Fourier transform. This result provides a general expression as a tool for analyzing complicated systems involving several lenses and mirrors separated by arbitrary distances; for this class of system it is sufficient to specify the ray transfer matrix and the order of fractional Fourier transform to characterize the system completely.

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1. Introduction

The fractional Fourier transform, which is an extension of the conventional Fourier transform to the fractional order has been introduced into the mathematics literature by Namias[1] in 1980; recently, Mendlovic, Ozaktas and others authors [2-6] introduced a new tool for image analysis in optics; since then, its properties, optical implementation and applications have been studied extensively. An operational definition of fractional Fourier transform in optics and the interpretation of fractional order Fourier transform as the mathematical representation of Fresnel diffraction was stated. Lohmann gave a different definition of the fractional Fourier transform that is based on the Wigner distribution functions. The purpose of this paper is to formulate the fractional order Fourier transform operator; this formula gives the direct relationship between input and output of multi-element optical system.

The study of the ray transfer matrix is particularly useful to simplify the analysis of optical situations; the Collins formula, is a diffraction integral formula for complicated optical system and establishes a bridge between the ray optics and wave optics under paraxial approximation. We show how the combinations of the ray transfer matrix, the Collins formula and the fractional order Fourier transform, result in a new approach suitable for the study of optical structures, where the propagation of light can be viewed as a process of continual fractional Fourier transformation.

2. Ray transfer matrix

Under paraxial conditions the properties of rays in optical system can be treated with the elegant formalism of the ray transfer matrix; a paraxial ray in a given cross section of an optical system is characterized by its distance of x from the optic axis and slope x'. If this slope is assumed small, the ray path through any given structure depends on the structure’s optical properties, of the structure and on the input conditions. In this situation the relation between the input and output parameters is given for:
\[ \begin{pmatrix} x_2' \\ x_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_1' \\ x_1 \end{pmatrix} \tag{1} \]

The \(ABCD\) matrix is called the ray transfer matrix and generally speaking the determinant is unity.

3. The fractional Fourier transform and the Collins formula

From plane \(U_A(\xi, \eta)\) to \(U_P(u, v)\), the diffraction field amplitude can be written in Collins diffraction integral equation; the Collins formula in space-domain which gives the relationship between the input complex amplitude \(U_A(\xi, \eta)\) and the output one \(U_P(u, v)\) can be rewritten as:

\[
U_P(u, v) = -\frac{i}{\lambda B} \exp \left( i\pi D \left( u^2 + v^2 \right) \right) \int_{-\infty}^{\infty} \exp \left( i\pi A \left( \xi^2 + \eta^2 \right) \right) \exp \left( -\frac{2\pi i (u \xi + v \eta)}{\lambda B} \right) U_A(\xi, \eta) \xi d\eta \tag{2} \]

Illuminating the input plane \(U_A(\xi, \eta)\) with the spherical wave of the radius \(R_1 \over A > 0\), after a little algebra; the equation (2) can be written in a considerably simpler manner in terms of the fractional order Fourier transform given by:

\[
U_P(u, v) = \frac{2\pi \sin \alpha}{i \lambda B} \exp \left[ \frac{D}{B} - \frac{\cos^2 \alpha}{A} \left( \frac{B}{R_1} \right) \frac{i\pi}{\lambda} \left( u^2 + v^2 \right) \right] \exp \left[ -i \left( \frac{\pi}{2} - \alpha \right) \right] \mathcal{F}^{\alpha} \left[ U_A(\xi, \eta) \right] \tag{3} \]

Where:

\[
\mathcal{F}^{\alpha} \left[ U_A(\xi, \eta) \right] = \frac{\exp \left[ i \left( \frac{\pi}{2} - \alpha \right) \right]}{2\pi \sin \alpha} \exp \left( -i \frac{\pi}{2 \tan \alpha} \left( \xi^2 + \eta^2 \right) \right) \int_{-\infty}^{\infty} \exp \left( \frac{\pi i (u \xi + v \eta)}{\sin \alpha} \right) U_A(\xi, \eta) \xi d\eta \tag{4} \]

A fractional Fourier transform relation \(\mathcal{F}^{\alpha}\) of order \(n_\alpha\) between the output field complex amplitude \(U_P(u, v)\) and the input field complex \(U_A(\xi, \eta)\), can be obtained with \(\alpha = \frac{\pi}{2} n_\alpha\); \((\alpha\) real parameter).

The phase factor it is a quadratic phase factor representing a quadratic approximation to a spherical wave, therefore the field complex amplitude over the output \(U_P(u, v)\) is over spherical surface with the radius \(R_2\) and proportional to the Fractional Fourier Transform of order \(\alpha\) of the input field complex amplitude \(U_A(\xi, \eta)\), Where:
Then it can be concluded that any ABCD optical system satisfying the relation (5) can implement a fractional order Fourier transform between spherical surfaces with $R_1$ and $R_2$ radius.

4. General optics system analyzed as fractional order Fourier transform.

Equation (5) implies that the condition for a fractional order Fourier transform is that $B \neq 0$; in this situation the field amplitude $U_p(u, v)$ represents the fractional order Fourier transform of the field amplitude $U_d(\xi, \eta)$, note that, just as with the wave optics operators, the ray transfer matrices should be applied in the sequence in which the structures are encountered if light propagates first through a structure with ray transfer matrix $M_1$, then through a structure with ray transfer matrix $M_2$, etc, with a final structure having ray transfer matrix $M_n$, then the overall ray transfer matrix for the entire system is $M = M_n \ldots M_2 M_1$.

4.1. Fractional order Fourier transform relation between the amplitude distributions of light on two spherical surfaces of given radii and ray transfer matrix.

Note that Eq (5) implies that $R_1 > B$ and $R_2 > \frac{B}{D}$; $D \neq 0$; then a fractional order Fourier transform relation exist between two spherical surfaces of radii $R_1$ and $R_2$. We can now write Eq (5) in the form:

$$\cos^2 \alpha = A \left(1 - \frac{B}{R_1}\right) \left(D - \frac{B}{R_2}\right)$$

(6)

Then it can be concluded that any ABCD optical system satisfying the relation (6) can implement a fractional order Fourier transform, we now discuss the consequences of this equation from five perspectives:

1. A fractional order Fourier transform relation exists between two spherical surfaces of radii $R_1$ and $R_2$ if and only $0 \leq A \left(1 - \frac{B}{R_1}\right) \left(D - \frac{B}{R_2}\right) \leq 1$.

2. Letting $\alpha = \pi$ (the parity transformation) it is possible to show that Eq (6) implies the well known imaging condition for multielement optical system.

3. Letting $\alpha = \frac{\pi}{2}$ (the usual Fourier transform) in Eq (6) we see that the complex amplitude distribution of the field in the spherical surfaces of radii $R_2$ is the standard Fourier transform of the field on the spherical surface of radii $R_1$. 
In Eq (6) we can easily find the confinement stability condition for multielement resonator; which coincides with the result obtained by self – consistence method for resonators. We can say that a fractional Fourier transform relation of order $\alpha$ between spherical surfaces of radii $R_1$ and $R_2$ implies the confinement stability condition for multielement spherical mirror resonator.

In accordance with Eq (3) and Eq (6) the diffraction integral evaluation of a multielement optical system can be easily carried out in terms of the $ABCD$ matrix.

In the particular situation when $\alpha = \frac{\pi}{2}$ the Eq (6) implies that

$$0 = A \left(1 - \frac{B}{R_1} \right) \left(D - \frac{B}{R_2} \right);$$

then the matrix element $A = 0$ and the result turns out to the usual Fourier transform.

### 4.2. Fractional order Fourier transform relation between planar surfaces.

We have seen that there exist a fractional order Fourier transform relation between two spherical surface; in Eq (6) we now consider that $R_1 \to \infty$ and $R_2 \to \infty$ (fractional Fourier transform between planar surfaces ) Eq (6) then becomes $\cos^2 \alpha = AD$. Letting $\alpha = \pi$ denote the order of transformation occurring from the input plane $U_A(\xi, \eta)$ to the output plane $U_P(u, v)$, we can write the imaging condition (for an inverted image) as

$$1 = AD.$$  

The usual Fourier transform corresponds to $\alpha = \frac{\pi}{2}$ and Eq (6) then becomes

$$0 = AD;$$

evidently when the matrix elements $A$ and $D$ are equal to zero we see that the complex amplitude distribution of the field in the output plane $U_P(u, v)$ is the Fourier transform of the field in the input plane $U_A(\xi, \eta)$.

### 4.3. Fractional order Fourier transform operator.

According to equation (3) only one operator is used to express field transfer by diffraction for an optical system described by an $ABCD$ matrix; the relationship between the input and
output functions can be established by Eq (3). To understand how to use this operator, consider an spherical emitter \( U_A(\xi, \eta) \) of radii \( R_1 \) followed by section of free space \( d_1 \), followed by lens of focal length \( f_1 \), followed by section of free space \( d_2 \), followed by lens of focal length \( f_2 \), followed by section of free space \( d_3 \), and spherical receiver \( U_p(u, v) \) of radii \( R_2 \) (Fig. 1). The corresponding \( ABCD \) matrix reads as:

\[
\begin{pmatrix}
1 & -d_2 + 1 + \frac{d_2}{f_2} & d_1 + d_2 - \frac{d_1 d_2}{f_1 f_2} & 1 - \frac{d_1}{f_1} - \frac{d_2}{f_2} + \frac{d_1 d_2}{f_1 f_2} \\
-\frac{1}{f_1} + \frac{d_2}{f_2} & 1 - \frac{d_1}{f_1} + \frac{d_2}{f_2} + \frac{d_1 d_2}{f_1 f_2} & \frac{d_1}{f_1} - \frac{d_2}{f_2} + \frac{d_1 d_2}{f_1 f_2} & 1 - \frac{d_1}{f_1} + \frac{d_2}{f_2} + \frac{d_1 d_2}{f_1 f_2}
\end{pmatrix}
\]

(7)

According to operator in equation (3), the relationship between the complex amplitude distribution on the spherical emitter \( U_A(\xi, \eta) \) with radii \( R_1 \) and the complex amplitude distribution on the spherical receiver \( U_p(u, v) \) with radii \( R_2 \) can be established as:

\[
U_p(u, v) = \frac{2 \sin \alpha}{\pi} \left( \frac{d_1 + d_2 - \frac{d_1 d_2}{f_1 f_2}}{d_1 + d_2 + \frac{d_1 d_2}{f_1 f_2}} \right) \exp \left[ \frac{i \pi (u^2 + v^2)}{d_1 d_2 (R_2)} \right] \exp \left[ -i \left( \frac{\pi}{2} - \alpha \right) \right] \left| U_A(\xi, \eta) \right|^2
\]

(8)

Given \( R_1 \) and \( ABCD \) matrix; if we wished to design a fractional Fourier transform system with specific order \( \alpha \) using Eq (5) we can obtain \( R_2 \).

Given \( R_1, R_2 \) and \( ABCD \) matrix if we wish to design a fractional Fourier transform system using Eq (6) we can obtain the specific order \( \alpha \).

In fig 1. alternatively, let us consider an pair of planar surfaces with \( R_1 \to \infty \) and \( R_2 \to \infty \), it is now possible derived the well known Fourier transforming properties of lenses by Goodmann (\( d_3 = 0 \) and \( f_2 \to \infty \)), the canonical assemblies by Lohmann, (\( d_1 = d_2 = 0 \), \( f_1 = f \), and \( f_2 \to \infty \) type-I setup); (\( d_1 = d_2 = 0 \) and \( f_1 = f_2 = f \) type-II setup), the imaging condition (\( \alpha = \pi \), \( d_3 = 0 \) and \( f_2 \to \infty \)) optical system as performing two consecutive fractional Fourier transform operations (\( d_2 = d_1 + d_3 \)); condition for \( U_p(u, v) \) to be the coherent image of \( U_A(\xi, \eta) \) (\( \alpha = \pi \)) and \( U_p(u, v) \) to be the standard Fourier transformation of \( U_A(\xi, \eta) \) (\( \alpha = \pi / 2 \)).

This result shows that the fractional order Fourier transform operator Eq (3) provide a convenient and systematic technique for analysis of optical system described by an \( ABCD \) matrix.
5. Summary

In this paper using the Collins formula, the ray transfer matrix and the fractional order Fourier transform we have derived the fractional order Fourier transform operator; in addition this operator provide a new way of analyzing optical system involving several lenses and mirrors separated by arbitrary distances.

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References

Optical Engineering at Rose-Hulman Institute of Technology: ABET Accreditation with EC 2000

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Abstract: Rose-Hulman has a history of meeting the need for optical engineers via the Applied Optics Programs since 1983. We have changed our degree program to Optical Engineering and will seek ABET accreditation. The present paper will deal with the step taken to accomplish this and define the mission of the degree program.

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1. Introduction

Rose-Hulman has a long history of graduating optical engineers via the Applied Optics Programs and the name change to Optical Engineering will in fact reinforce the idea that we are educating our students in applications of optics to deal with real world problems and practice the profession optical engineering. Most of our students have expressed an interest in obtaining an optical engineering degree due to the level of optics education which is heavily lab and project oriented. Further the departmental advisory board that consists of top professionals from the optical industry and education strongly endorsed the name change to optical engineering. This science department is now optimally positioned to make this timely change to the degree name as well as seek ABET accreditation. In this paper we will discuss several steps that needs to be taken to fulfill the EC2000 criteria set by ABET.

2. EC2000 ABET Accreditation and the procedures adopted at Rose-Hulman

RHIT is an undergraduate science and engineering institution although we have an active masters level graduate program in many areas. The Department of Physics and Optical Engineering presently offers B. S. degrees in Optical Engineering, Engineering Physics, and Physics. Further, certificates in semiconductor materials as well as image processing enables the student to learn diverse topics. The multidisciplinary field of optics in the undergraduate curriculum is facing revolutionary changes, as optical techniques become the standard tools for industrial inspection and as optical components become standard items in consumer product. This necessitates the need to improve the curriculum from the traditional science course sequence and match the need for more applied and engineering nature of the courses. ABET’s intent of criteria states that a curriculum in engineering should have to assure adequate foundation of science, humanities and social sciences, engineering sciences, and engineering design methods. This program is not intended as a supporting role in optical engineering but provides the basic practices of optical engineering. It also states that the specific program must have appropriate expertise, which we have, is further strengthened by the ECE department’s hire in the optics area. There are various factors that need to be fulfilled as we look at the criteria of EC2000. We have highlighted all the major categories and its bulleted subsection and show the similarities between EC2000 and the optical engineering curricula at Rose-Hulman. We will also point out places where action needs to be taken to fulfill the criteria.

3. The need for optical engineering:

The last two decades have seen a remarkable increase in the application of optics-based technology. The applications cover a very diverse list of areas and the demand for people with optical engineering
background in the industrial sector is very large and will most likely increase. Since most of the breakthroughs related to optical technologies have occurred relatively recently, the possibilities are practically endless.

Many industries are utilizing the principles of optical engineering in their industrial processes for the development of new products and component of new products. The developments in this area are occurring very quickly and companies need people with background in optical engineering in order for them to remain competitive. Some of the areas gaining the most publicity from this technology are medical diagnostic imaging, laser surgery, quality control devices, imaging, telecommunications, and fiber optics technology. These and many more areas require expertise in optical components as well as systems level understanding of these components.

Many journals (Laser Focus World, Photonics Spectra, Optoelectronics, Optics and Photonics News, etc.) dealing with optical technologies forecast a deficiency in the number of optical engineers in this country. As the potential benefits of optical technologies increase more optical engineers will be needed to bring about practical and useful devices.

Rose-Hulman Institute of Technology (RHIT) has a history of meeting the need for optical engineers via the Applied Optics (AO) Programs. In fact, many of our AO graduates have been employed as optical engineers. However, the name applied optics is not well understood in industry and has been regarded more as fundamental studies in optics as opposed to the applications of optics to technical problems. The name change to Optical Engineering will reinforce the idea that we are educating our students in applications of optics to deal with real world problems and practice the profession optical engineering. The AO idea does not carry the same connotations in industry as Optical Engineering. This has hindered some of our students from obtaining employment with some companies that are not aware of our program.

The AO program currently meets all of these goals. Most of our AO students have expressed an interest in obtaining an optical engineering degree. Further the departmental advisory board that consists of top professionals from the optical industry and education strongly endorsed the name change to optical engineering. The department is now optimally positioned to make this timely change. The change to optical engineering and the requisite changes in the curriculum would meet the desire of most of our AO students and the demand from industry. Therefore, we propose that the name of Applied Optics in the B.S. and M.S. be changed to Optical Engineering.

4. Impact statement:

At RHIT there are 10 departments consisting of four science departments (mathematics, chemistry, biology, and physics & optical engineering), four engineering departments (Mechanical, chemical, civil, electrical & computer), computer science, and humanities & social science department. As these 10 academic departments are closely tied in their teaching and course development activity we have a policy of developing impact statement that indicates how a new or modified program affects other departments. It is necessary that an impact statement be written that addresses the staffing of the program and how it affects other departments, in terms of teaching and student enrollment. We generated such impact statements and found minimal influence of the degree name change on other departments.

5: Background

It is well understood that optics education in the undergraduate curriculum is multidisciplinary and
involves more engineering in its education than science/physics degree. We are faced with the task of designing a curriculum to meet not only the growing needs of market trend but also to make the students learn the essentials. The students need to gain knowledge in a broad range of fields from pure physics to almost every discipline of engineering but appropriately staggered by designing courses that have specific outcomes. This should not essentially be focused on the methodology of teaching but on a broader level of evenly distributed but reinforced learning styles for the students. This task is significantly difficult in the optics curriculum because optics courses are usually a blend of new technology, engineering and physics. At RHIT, this concept has geared us to evaluate the traditional sequence in a course with laboratory in terms of information content and student outcomes. Overall, laboratory experiments are designed to reinforce concepts for understanding the basic scientific ideas of a particular course along with the necessary experimental skills. RHIT’s optics program has evolved gradually to mix the two worlds with the introduction of project-based courses that awaken the scientific curiosity as well as the engineering creativity [1-3]. There has also been a focus to enable the students to employ their optics and scientific knowledge to build products as well. We are in a process of constantly restructuring the program to meet the challenges of tomorrow by carefully assessing the needs of the students, the engineering community and the market place.

6: ABET accreditation for the Optical Engineering program

The multidisciplinary field of optics in the undergraduate curriculum is facing revolutionary changes, as optical techniques become the standard tools for industrial inspection and as optical components become standard items in consumer product. This necessitates the need to improve the curriculum from the traditional science course sequence and match the need for more applied and engineering nature of the courses. As educators, we are faced with a task of designing a curriculum to meet the growing needs of market trend. In that regard we have proposed the name change along with appropriate curriculum to meet the market requirement.

ABET stands for Accreditation Board for Engineering and Technology. ABET’s intent of criteria states that a curriculum in engineering should have to assure adequate foundation of science, humanities and social sciences, engineering sciences, and engineering design methods. The intent is to prepare students for the practice of engineering at a professional level. This program is not intended as a supporting role in optical engineering but provides the basic practices of optical engineering. It also states that the specific program must have appropriate expertise, which we have, is further strengthened by the ECE department’s hire in the optics area. There are various factors that need to be fulfilled as we look at the criteria of EC2000. We have highlighted all the major categories and its bulleted subsection and show the amount of similarities between EC2000 and the optical engineering curricula. We will also point out places where action needs to be taken to fulfill the criteria

In EC2000, specialty programs like optical engineering fall under the program criterion as nontraditional programs. In the nontraditional programs few examples are Engineering sciences, Material science, Mechantronic engineering, Engineering physics, Engineering and public policy, and Optical engineering as well. There is only one school in US that has an accredited program in optical engineering and one that is in the process of getting accreditation even though there are couple of them that do not have accreditation. We in the Physics and Optical Engineering (PHOE) department are fortunate to have the Electrical and Computer Engineering (ECE) department as our collaborator in this direction. We propose to offer the Optical Engineering course from the PHOE department along with suitable courses from the ECE and other engineering departments. ABET has presently modified the accreditation policy for all nontraditional engineering program and they all fall under one umbrella as engineering program in their EC2001-2002 document. There is no special classification of a nontraditional engineering program anymore.
The restrictions such as having faculty advisors from engineering departments and courses needed to be taken from engineering departments for a classified nontraditional program has been lifted. The documents with bullets in this paper are generated from EC2000 and is identical to EC2001-2002 criteria [4] except that the section on nontraditional program criteria has been removed. We show in the highlighted sections how we satisfy each of the criteria and also methods that will be taken to fulfillment them as we get the program into full swing. It should be noted that as far as optical engineering program was concerned prior to EC2001-2001, we had to satisfy two criteria under nontraditional engineering program. The two criteria were: i) In institutions with a substantial number of faculty members educated as engineers and teaching in other departments, one or two faculty members should be responsible for guidance as coordination of the non traditional program and ii) must have at least one year of course taught by engineering faculty. These two criteria were addressed in our first response to faculty members in the institute. However, since then we have modified our documents. We still believe that it will help the program to have one or two faculty from the engineering department be advisors to the program and therefore we have included advisors from the ECE department.

We present a broad overview of the ABET criteria as applicable to optical engineering program at Rose-Hulman.

ABET CRITERIA:
I.C.1 faculty:
   a. Faculty that can give overall scholarly atmosphere
   b. Level of academic training, diversity of its background, effective teaching, degree of participation in professional and scientific societies
   c. Must have at least three full time faculty
      The definition of an engineering faculty is broad and there are various criteria that are used to judge optical engineering faculty. The overall competence of faculty is judged by factors such as education, diversity of backgrounds, engineering experience, teaching experience, ability to communicate, enthusiasm for developing more effective programs, level of scholarship, participation of professional societies, and registration as professional engineers. A large number of the OE faculty members have engineering, design, and industrial experience. In addition we have faculty advisors from the electrical and computer engineering department (ECE) who will also collaborate in developing courses jointly as well.
   d. Stability, continuity and morale of the faculty
   e. Teaching load must be consistent
   f. Curriculum and career advising
      All the departments at RHIT meet criteria d-f.
I.C.2 Curricula Objective:
   a. Capability to delineate and solve in a practical way of society that are acceptable to engineering treatment.
   b. Sensitivity to the socially-related technical problems
   c. Understanding of the ethical characteristics of the engineering profession and practice
   d. Understanding of the engineer’s responsibility
   e. An ability to maintain professional competence
      We have shown that we were and are fulfilling all the above requirements with the change in the curriculum. This is documented in the through several of the report published by the department.
I.C.3. Curricula content:
   I.C.3.d.(1). One year of appropriate combination of mathematical and basic sciences
   I.C.3.d.(2). One-half year of humanities and social sciences
I.C.3.d.(3). One and one-half year of engineering topics

The Optical engineering curricula provides this integrated educational experience that identifies with the I.C.3 of the Accreditation commission. It is very well documented that at RHIT the first two bullets in the Optical Engineering curricula are accomplished and the requirement is to show that we will fulfill the third requirement in engineering topics. Therefore we will omit the sections I.C.3.d.(1) involving science and math requirements and I.C.d.3.(2) involving humanity and social science requirements. Our curriculum has a strong foundation in engineering and from the content and breadth standpoint it compares well with other accredited optical engineering degree program. Presently ABET has accredited two optical engineering degree programs in the nation.

Engineering topics include engineering sciences and design.
I.C.3.d.(3) Engineering sciences:
I.C.3.d.(3) Engineering design:

a. Engineering sciences should be developed with the mathematics and basic sciences as it roots.
   All the optical engineering courses are developed with mathematics and science as foundation courses.

b. Process of devising a system, component, or process to meet demand
   We have developed several courses which meet this requirement.

c. Design experiences should be taught in section sizes that are small enough
   We have shown that there are over seven courses that have very strong design components. Some of the courses are already accepted as design for some engineering departments as well. The Optical engineering design course is well documented from some of our publications in OPN as well as in SPIE proceedings [1-3].

d. Self study questionnaire should be able to discern the goals of the program and the logic of the selection of the topics
   We plan to initiate this process once we have OE degree program.

e. Drafting skills
   OE students will get this from graphical communication course.

f. Appropriate laboratory experiences
   All OE courses are very lab intensive and have 4 to 8 labs in a course.

g. Knowledge of probability and statistics to engineering problems
   We are thinking of including one such course but some of these topics and concepts are already covered in our laboratory courses.

h. Competence in written and communication skills
   The OE students already take technical communication.

i. Ethical, social, economic, and safety considerations in engineering practice.
   The Humanities and Social Science requirement at RHIT fulfills some of these requirements. These issues are also covered in the project courses and laser related courses. Every laboratory course has laser safety component associated with it.

I.C.4. Student Body

a. Quality of the students
b. Policies for accepting transfer of credits
c. Example works of exams, homework problems, laboratory exercises, design, and reports

d. Record of what the graduates are doing after graduation
   We have started the several of the procedure in the department as in the other engineering departments at RHIT including assessment of several of the soft skills. We have looked into several of the self-study books and will generate a standard procedure
for keeping records of class activities and alumni survey.

I.C.5. Administration:
   a. Capable faculty
   b. Selection, supervision, support of faculty, and supervision of students
   c. Constructive leadership
      We meet this entire requirement.

I.C.6. Institutional facilities:
   a. Adequate physical facility
   b. Library support
   c. Computer facility
   d. Laboratory facility
      We meet this entire requirement.

I.C.7. Institutional Commitments:
   a. Organizational structure of the University should support the engineering mission
   b. Sound physical policy
   c. Provide facilities to support engineering program
      We have received endorsement from several of our constituencies such as Alumni, the departmental advisory board, and the administration. The program was approved by the highest body, the curriculum committee in the school that approves all curriculum issues. Several soft core criteria for the program have been assessed and all the course materials are being documented. We will be sending surveys to graduated optical engineering alumni in 2004-2005. Several of the assessment of student learning is being done through e-portfolio at Rose-Hulman. The students submit several of their work on a specific outcome and during the summer faculty raters then evaluate the student submission. The student is then given a response as to whether he met the criteria or not. The results are then sent to the department which then used to close the loop on several of the learning objectives.

7: Acknowledgement

The paper presented here has been reviewed by the department faculty on many occasions and the authors would like to thank the PHOE department faculty for their suggestions and input in the preparation of this article. Further all these developments in education in optics is not possible without the input and feedback from our optics students. They have inspired us as faculty and provided the energy to work on the process of improving optics education and we thank all of them.

8: References

The computer training program on tomography

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Abstract: Computer training program was developed to learn the students, studying plasma diagnostics methods, the principles of computer tomography and some algorithms of reconstruction of 3D plasma parameter distributions. The program allows to simulate some spatial distribution of plasma emission, to calculate projections of non-uniform plasma objects and to demonstrate visually the result of restoration of axially symmetric and asymmetric objects at the chosen number of projections. The software allows to simulate the noise distortion of projections and thus to show the dependence of reconstruction accuracy on the number of projections, noise level and reconstruction algorithm.

Key words: training program, tomography, plasma, help system, projection, iterative methods, analytical methods, computer simulating, filtration by convolution.

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Introduction

One of the modern methods of plasma diagnostics is the method of the reconstructive computer tomography. This method allows determining the local characteristics of researched heterogeneous plasma objects with an enough high degree of accuracy that gives broad opportunities in understanding physical processes in these objects. The quality of the reconstruction essentially depends on such factors, as the number of directions of observation, the number of detecting devices, the stability of the algorithm to noises.

The computer simulation allows determining the optimal conditions of the statement of the tomography experiment.

In this connection there was a task to create the training software, which would allow acquainting a student with some algorithms of the computing tomography and with the conditions of the realization of the tomography experiment.

The developed training program «Tomography 1» allows:

1. to calculate projections of mathematical models of heterogeneous plasma objects,
2. to visually demonstrate the reconstruction of axially symmetric and asymmetric objects at the chosen number of projections (perspectives of supervision),
3. to add noise on projections,
4. to represent the results of reconstruction in a three-dimensional form and to have the possibility to normalize it,
5. to determine the accuracy of restoration,
6. to analyse the dependence of the accuracy of restoration of an object on the number of projections and noise level.

Our software contains three algorithms of computer tomography: "method of reverse projections", "wavelet filtration" [1] and "the filtration by convolution" based on Fourier transform [1].

In spite of the fact that the method of reverse projection restores the image with significant false signals and now is used in rare cases, it is cited here due to its importance among the basic precise methods.

The method of reverse projections with the filtration is used in many modern X-ray diagnostic tomographs and thus plays the special role from the practical point of view.

Also in the software two iterative methods of tomography are realized: an algebraic method of restoring (ART-Algebraic Reconstruction Techniques) or a beam by beam correction and iterative method of least squares (ILST - Iterative Least-Squares Technique) or simultaneous correction [2].
The demonstrating the work of both analytical and iterative methods gives more ideas in computing tomography since they were widely introduced in various applications and played the important role in development of tomography.

The program was developed in Borland Delphi 7.0. "Tomography 1" requires operational system Microsoft Windows 95/98/2000/XP on IBM PC the AT-compatible computer with the processor above Celeron 266. At least, work of the program needs 1 Mbyte of free disk memory (6 Mbytes including help instructions). The videodriver must be set up in High Color or True Color mode. The program uses standard library OpenGL.

1. Tomography application to plasma diagnostics

For determination of local plasma parameters - electron, ion and atom densities and energy distribution functions - such optical characteristics of elementary plasma volume as the refraction index $n(\lambda, r)$, the absorption coefficient $k(\lambda, r)$, the spectral emissivity $\varepsilon(\lambda, r)$ can be used. Here $\lambda$ - wavelength, $r$ - coordinate of some point in plasma volume.

But these values are not measurable in inhomogeneous plasma. Only following parameters of a source can be measured:

- $b(\lambda, r)$ - spectral surface radiance,
- $Q(\lambda, r)$ - phase difference,
- $\tau(\lambda, r)$ - optical thickness of plasma.

The integration in all cases is conducted along "of a ray of observation" U, and scanning is possible along a perpendicular direction V, i.e. all listed integrated values can be considered as a projection and to restore local characteristics $n(\lambda, r), k(\lambda, r), \varepsilon(\lambda, r)$ one has to use tomography methods.

2. The description of the program and its applicaiton

At the start of the program "Tomography 1.exe" there is a main window on a screen - "Tomography 1" (Fig. 8.), on which the components to set parameters and to control the work of the program are located:

The «File» menu (Fig. 2.1.) of the main window allows to quite the program (Exit) and to save of the obtained pictures in BMP a format (Save graph).

From the «Options» menu (Fig. 2.2.) the modules for the determination of a mathematical model (Model …), for the presentation of the given model in three dimension kind (Show model …), for determination of noise level (Noise level …), for parameter setup of restored object (Set-up of an image …) and for information about accuracy of object’s restoring (Error …) are called.

From the «Help» menu (Fig. 2.3) the in-depth help of the program’s description "Tomography 1" and methodical information on tomography (concept of tomography, mathematical description of tomography methods, features of plasma objects tomography etc.) are called.

For deriving submission about conditions of tomography experiment realization and in-depth inspection with some algorithms of computing tomography, first of all it is necessary for student to study closely a reference system called from the program (Fig. 2.3.).

The file of help represents itself some chapters with methodical information on tomography, and also contains the description of the program (Fig. 2.4.).
From a reference system student learns, for example, that the methods computing tomography can be divided into two main classes: analytical and iterative [2,3].

The analytical methods are based on point mathematical solutions of the image reconstruction equations. A Fourier transform and Radon's transform are used in a basis of majority of them. All analytical methods of image reconstruction theoretically are equivalent; however, they differ by implementing procedure.

The iterative methods of image reconstruction use approximation of restored object by an array of cells of an equal denseness representing themselves unknown quantities connected by a system of the linear algebraic equations, free terms of which are the readout on a projection. The set of equations are decided by iterative methods and it has denominated the given class of restoring methods. Some iterative methods of image reconstruction now are known. They differ from each other on a sequence of entering of single-error corrections during iteration. Among them three methods are most known and common: an algebraic method of restoring (ART), method of simultaneous iterative restoring (SIRT) and iterative method of least squares (ILST)[2].

After an inspection of a theoretical part, student is offered to begin immediately realization tomographic experiment on the basis of numerical simulating.
For this purpose from the «Options» menu of a main window, the module for the task of a mathematical model (Model …) (Fig. 2.5) is called. Student is offered to use various combinations a Gaussian distribution in quality of enough smooth model distributions simulating spatially an inhomogeneous medium. In the window user selects a combination of functions of the Gauss (up to 9 pieces), sets factors («a», «b», «c») and installs maximum (Xmax, Ymax) and minimum (Xmin, Ymin) significances on axeses. The button «Show model» is pressed further for show created model in the separate window «Model» (Fig. 2.6.).

In a right upper angle of the «Model» window (Fig. 2.6.) the raster of a model (Raster NxN) is underlined, «Turn of a system» - shows turn angles of a frame («X», «Y», «Z»). Simple movement of the Mouse stipulates the possibility of a turn of a model. The button «Show» should be pressed in case of redrawing the picture. Normalization is selected, if it is necessary to realize a normalization of a model (at determination of an error of restoring normalization happens automatically). There are the same items in the menu «File», «Options» «Help» as in the main window.

After the model is given, it is necessary to return to the main window (Fig. 2.9.) (It is open all the time). The components located on it allow conducting numerical experiment.

Student is offered to look through projections from the created mathematical model. In
the block «Parameters of a projection» (Fig. 2.7.), user sets number of samples - «samples on a projection», the turn angle of a frame «Turn angle» and presses a button «Projection». For a conclusion of nucleus convolution function, the nucleus (Nucleus of Ramachandran or MHAT (Mexican hat) wavelet) is selected and the button «Nucleus» is pressed. (Fig. 2.8, 9). For survey of a nucleus convolution with the introduced projection «Convolution» is pressed (Fig. 2.10, 11). For it student should compare obtained outcomes and on the basis of information from a reference system qualitatively predict exactitude of restoring by various algorithms.

Fig. 2.8. A nucleus Ramachandran.  
Fig. 2.9. MHAT wavelet.  
Fig. 2.10. A convolution of a projection with MHAT wavelet.  
Fig. 2.11. A convolution of a projection with a nucleus Ramachandran.
For direct restoring of a model there are set in the block «Reconstruction» (Fig. 2.12):

Raster of tomogram «Raster tomography NxN»; number of projections «Amount of projections M»; an angular pitch «Angular pitch»; algorithm of restoring «Algorithm»; it is underlined whether to conduct a normalization «Normalization» and then the button «Reconstruction» is pressed.

For displaying a restored object the button «Show» is to be pressed.

For best understanding of algorithm operating, student should implement a series of experiments varying parameters of restoring, should make the comparative qualitative analysis.

For realization of the quantitative analysis, it is necessary from the «Options» menu (Error …) of a main window to call the module (Fig. 2.13.) of information conclusion about accuracy of object reconstruction (Error). Quality measure of reconstruction is an error of restoring magnitude $\Delta$ (1), which is determined as root-mean-square norm of a restored solution deviation $f(x_i, y_j)$ from point $f_0(x_i, y_j)[4]$

$$\Delta = \frac{\left(\sum_i \sum_j (f(x_i, y_j) - f_0(x_i, y_j))^2\right)^{1/2}}{\left(\sum_i \sum_j (f_0(x_i, y_j))^2\right)^{1/2}} \cdot 100\%$$

As the independent task student is offered to conduct a series of experiments and study the dependance of reconstruction accuracy on the number of projections and to determine whether in all algorithms the magnification of projections number leads to increasing of restoring exactitude.

Images with restored models by various algorithms are indicated below.
Fig. 2.15. A method of a return projection with a filtration by convolution (error 4.787 %, nucleus Ramachandran).

Fig. 2.16. A method ART (error 15.796 %, 10 iterations).
In the program some noises may be add to projection (Menu «Options», line «Noise level»). Amplitude of a noise is determined as the specified by user percent (Fig. 2.18.) of current value of a projection.

Student is offered to conduct a series of experiments, imposing on a projection noise, to make the comparative qualitative and quantitative analysis of obtained outcomes. Below for an example the outcomes of restoring from 2 % by a noise are indicated.

Besides the information about a general error of restoring, user is grantiven a possibility of evaluating visually the absolute error of each restored object element of object «The absolute error» (Fig. 2.13.).

The absolute error is removed as the certain field of errors (Fig. 2.19.).

The possibility of maximum visualizing the outcomes of numerical experiment is grantiven to student, who is changing parameters of restored object map (Menu «Options», Set-up of an image …) (Fig. 2.20.) «Points» - to map object by points (Fig. 2.21.) (thus, the computing resources are essentially saved); «Triangulation» - triangulation of object; «Halftints» - to map object by halftints (Fig. 2.22.); «Site» - to map a grid; «Axes» - to show axeses of coordinates; «Grid» - to show the basis.
Now program is successfully used for training students in program «Optical methods of plasma diagnostics ».

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Liquid crystal experiment for undergraduate engineering students

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Abstract: An undergraduate experiment to investigate the optical properties of liquid crystals (LC) is described. The target students are final-year undergraduates pursuing an advanced optoelectronics course at the Electrical and Computer Engineering Department of the National University of Singapore. In the first part of the experiment, the retardation of light by a LC cell is determined by analyzing the polarization state of light passing through the cell. In the second part, the time response of the LC molecules is obtained by applying a time-varying voltage to the LC cell. The objectives of the experiment are to i) provide a hands-on experience of an optical source-modulator-detector system, in response to the needs of industry, ii) illustrate a practical application of Jones matrix analysis, iii) establish a link between the molecular properties of an LC medium and their optical properties and iv) show how the material properties of a LC material may influence its use in display devices.

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OCIS codes: (160.3710) Liquid crystals; (230.2090) Electro-optical devices; (260.1440) Birefringence

1. Introduction

An advanced course on optoelectronics [1] has been taught to final-year undergraduates at the Electrical and Computer Engineering Department of the National University of Singapore for 15 years. The course is designed to enable students to acquire understanding of the fundamental principles underlying device operation, as well as the technological knowledge relevant to the photonics-related industry. The course contents are constantly updated based on developments in the photonics technology.

Broadly, the course covers the basic physics of light emission, modulation and detection, in semiconductors, electro-optic crystals and liquid crystals (LC). In recent years, greater emphasis has been placed on the study of LC. This trend is in tandem with the growth of the LCD (liquid crystal display) manufacturing activity in Singapore, as highlighted by the recent investment by Toshiba and Matsushita, worth USD1.1 billion, to produce advanced poly-Si thin-film transistor LCDs in Singapore [2]. The course lectures on LC adopt a multi-disciplinary approach in presenting this large and rapidly developing field. They cover (a) a brief introduction on the basic structural and chemical properties of LCs; (b) the physics of light interaction with the electric dipole of the LC molecule (resulting in birefringence) and of the elastic, viscous and electric forces [which give rise to the twisted nematic (TN) configuration]; (c) the operation of a TN cell which is a key component of a LCD and (d) the large-scale integration and addressing of these cells in a LCD.

The class experiment described in this paper provides the necessary practical complement to the lecture materials. Through the experiment, students will investigate how a monochromatic light beam is modulated by a LC material, and how to characterize this modulation using an optical detection system. The results of the experiment will re-emphasize the theory concerning the birefringence property of LCD which is central to the TN cell operation. The student will also study the time response of the LC molecules and relate this to the forces holding the LC molecules together.

2. Overview of Liquid Crystals

Although liquid crystals were discovered in 1888 by Renitzer, its use in electronically addressed displays dates back to the 1960’s only. A breakthrough for LC applications occurs with the discovery of MBBA in
the late 1960’s [3], which exhibits the nematic phase at room temperature. This was followed by the discovery of cyanobiphenyls [4], which are more stable to heat and light and have strong birefringence property, thus paving the way for LC display applications. On the technology side, the development of the TN cell in 1967 resulted in LC readout displays in calculators, watches and other devices. Since then intensive research in academia and industry has resulted in the development of new types of LC materials such as super-twisted nematic and polymer-dispersed LC materials, with enhanced properties. Running parallel to this materials research is the rapid progress in LCD technology, such as the development of poly-Si thin-film transistors (TFT). These advances have led to a dramatic fall in the price of LC flat-panel displays. It is estimated that by the year 2005, flat panel displays, of which LCD forms a major proportion, will replace conventional cathode-ray tube (CRT) displays in personal computers and televisions. There is also an increasing demand for small LCDs in PDAs, mobile phones, digital cameras and other hand-held devices.

3. Objectives of Experiment

It is thus important to impart a practical knowledge of a basic LC modulator system to students in the optoelectronics course. For this purpose, a class experiment based on a LC system is designed.

The objectives of the experiment:

i) provide a hands-on experience of an optical source-LC modulator-detector system,

ii) provide a practical application of Jones matrix,

iii) establish a link between the molecular and optical properties of an LC medium,

iv) demonstrate external bias control of the LC optical properties – the basis of display applications.

4. Description of Experimental System

Fig. 1. Schematic diagram of optical set-up.

A photograph of the optical part of the set-up is shown in Fig. 1(a). The full experimental set-up consists of

i) Source: He-Ne Laser with monochromatic output at $\lambda=632.8$ nm.

ii) Modulators: Polarizer, Analyzer and $\lambda/4$ Waveplate

iii) LC (Retarder) Cell

iv) LC Controller Interface Card

v) Software for LC Controller Card

vi) Detector: Si Photodetector

vii) Digital Oscilloscope

viii) Vibration-free Optical Table

The source, modulator components, LC cell and photodetector are fixed on the optical table such that they lie along a single axis. The digital oscilloscope are connected to both the photodetector and the LC controller card, and displays both the voltage applied to the LC cell (input) and the intensity of modulated light (output) – see Fig. 1(b). The controller card and controller software enables the student to generate a periodic square wave voltage of variable amplitude across the LC cell (see Section 8).
5. Investigating the polarization state of light

**Method:**

The students are to set up the optical components and to pass the He-Ne laser light through the LC cell, sandwiched between the polarizer-analyzer pair. The polarizer axis is aligned at 45° to the fast axis of the LC cell (as indicated by the bold arrows in Fig. 3). An a.c. voltage of constant amplitude 5 V at 2 kHz frequency is applied to the LC cell. The angular dependence of the transmitted light is obtained by rotating the analyzer axis and recording the photodetector output at 10° intervals.

**Theory:**

Aligning the polarizer at 45° to the LC fast axis will ensure that the incident light beam is equally divided into two components, polarized respectively along the fast and slow axes of the LC cell. The LC cell exhibits birefringence, due to the anisotropic nature of the LC molecules. Thus, light polarized along the cell’s fast axis will experience a smaller refractive index compared to light polarized perpendicular to that axis. This results in a phase difference (or retardation) $\phi$ between the two polarizations. Depending on the value of $\phi$, light emerging out of the cell will be elliptically polarized to different degrees (full circular polarization if $\phi = \pi/2 + n\pi$, and linearly polarized if $\phi = n\pi$, where $n$ is an integer).

A mathematical representation of an elliptically polarized light is straightforward, i.e. $(1,\exp(\phi))^T$ in Jones matrix form. However, it is difficult to visualize in real life the characteristics of an elliptically polarized light. One significant difference between elliptically and linearly polarized light is that only the former does not undergo complete extinction at any point in the rotation $\theta$ of the analyzer axis, as shown in the sample experimental plot of Fig. 4(a).
Sample Results:

Analysis:

Jones matrix analysis is used to explain the observed results. First, consider the Jones vector for the elliptically polarized light ($\mathbf{v}_1$) formed by passing a linearly polarized light at 45° ($\mathbf{v}_0$) through the LC cell ($\mathbf{M}_i$), which introduces a retardation of $\phi$:

$$\mathbf{v}_1(\phi) = \mathbf{M}_i(\phi) \cdot \mathbf{v}_0 = \begin{pmatrix} 1 & 0 \\ 0 & \exp(i\phi) \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ \exp(i\phi) \end{pmatrix}. \tag{1}$$

Fig. 5. (a) shows an elliptically polarized light represented by $\mathbf{v}_1$ in Eq. (1). The $\mathbf{E}$-field vector traces out an ellipse with a major/minor axes at ±45° (bold line). (b) Polar plot of the calculated transmitted intensity. [Eq. (6)]. The enclosing ellipse is the polarization ellipse of the detected light.

To find the transmitted intensity through a rotated analyzer, one needs to obtain the Jones matrix for an analyzer oriented at an arbitrary angle $\theta$. For an analyzer along the $x$-axis, the Jones matrix is

$$\mathbf{A}(0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}. \tag{2}$$

For an analyzer at an arbitrary angle $\theta$, one has to perform a transformation using the rotation operator:

$$\mathbf{R}(\theta) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \tag{3}$$
Thus, after transformation, the Jones matrix for the rotated analyzer is given by

\[ \mathbf{A}(\theta) = \mathbf{R}^T(\theta) \cdot \mathbf{A}(0) \cdot \mathbf{R}(\theta) = \begin{pmatrix} \cos^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \sin^2 \theta \end{pmatrix}. \] (4)

The transmitted light \( \mathbf{v}_2 \) after passing through the analyzer is then

\[ \mathbf{v}_2(\phi) = \mathbf{A}(\theta) \cdot \mathbf{v}_1(\phi) = \begin{pmatrix} \cos^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \sin^2 \theta \end{pmatrix} \begin{pmatrix} 1 \\ \exp(i\phi) \end{pmatrix} = \begin{pmatrix} v_x(\phi, \theta) \\ v_y(\phi, \theta) \end{pmatrix}. \] (5)

The photodetector detects a time-averaged signal of the transmitted light, i.e.

\[
\langle I_{\text{detected}} \rangle = \left( \text{Re} \left[ v_x'(\phi, \theta) e^{i\omega \gamma} \right]^2 + \text{Re} \left[ v_y'(\phi, \theta) e^{i\omega \gamma} \right]^2 \right)
= \frac{\omega}{2\pi} \int_0^{2\pi/\omega} \text{Re} \left[ v_x'(\phi, \theta) e^{i\omega \gamma} \right]^2 + \text{Re} \left[ v_y'(\phi, \theta) e^{i\omega \gamma} \right]^2 \, d\gamma
= \frac{1}{2} \left[ (\cos \theta + \sin \theta \cos \phi)^2 + \sin^2 \theta \sin^2 \phi \right].
\] (6)

The transmitted intensity and the corresponding polarization ellipse are plotted together in Fig. 5(b). The plot qualitatively agrees with the experimentally observed dumbbell-shaped variation as shown in Fig. 4. Additionally, both the calculated and experimental plots have their major axis at 45°. It is, however, not possible to quantitatively determine the retardation \( \phi \) directly from this angular dependence.

6. Determining the phase retardation due to LC cell

In this section, the student will perform two methods to quantitatively determine the phase retardation caused by the LC cell.

Method 1:

The same set-up as in Section 5 is used. The only difference is that the analyzer is fixed at 90° to the polarizer, and that a variable voltage \( V \) is applied to the LC from 0 to 10 V. The intensity of the detected light is then plotted against \( V \). A sample plot is shown in Fig. 6(a).

Analysis

As before, we first obtain the Jones vector for the transmitted light. We take the \( x \) and \( y \) axes to coincide with the polarizer and analyzer axes, respectively. Then, the LC cell, whose axis is oriented at 45° to the \( x \)-axis, is represented by the Jones matrix:

\[ \mathbf{M}_2(\phi) = \mathbf{R}(-\pi/4) \cdot \mathbf{M}_1(\theta) \cdot \mathbf{R}(\pi/4) \]

\[ = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \exp(i\phi) \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \]

\[ = \frac{1}{2} \begin{pmatrix} 1+e^{i\phi} & 1-e^{i\phi} \\ 1-e^{i\phi} & 1+e^{i\phi} \end{pmatrix}. \] (7)

Thus, the Jones vector of light after passing through the analyzer \( \mathbf{w}_2 \) is (\( \mathbf{w}_1 \) denotes the \( x \)-polarized light due to the polarizer):
\[ \mathbf{w}_2 = A(\pi/2) \cdot \mathbf{M}_2(\phi) \cdot \mathbf{w}_1 \]
\[ = \begin{pmatrix} 0 & 0 \\ 1 & \frac{1}{2} \end{pmatrix} \begin{pmatrix} 1 + e^{i\phi} \\ 1 - e^{i\phi} \end{pmatrix} \begin{pmatrix} 1 + e^{i\phi} \\ 1 - e^{i\phi} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 0 \\ 1 - e^{-i\phi} \end{pmatrix} \]

The corresponding \( \mathbf{E} \) field is then given by
\[ \mathbf{E} = \frac{E_0}{2} (1 - e^{i\phi}) e^{i\omega t} \mathbf{j}, \]
and the intensity is then
\[ I = |\mathbf{E}|^2 = E \times E^* = \frac{E_0}{2} (1 - e^{i\phi}) e^{i\omega t} \times \frac{E_0}{2} (1 - e^{-i\phi}) e^{-i\omega t} = \frac{E_0^2}{2} (1 - \cos \phi) \]
\[ \Rightarrow I = \frac{I_{\text{max}}}{2} (1 - \cos \phi). \]

The retardation is then given [taking into account the \( 2\pi \)-periodicity with retardation \( \phi \) as can be seen in Fig. 6(a)]:
\[ \phi = \cos^{-1} \left( 1 - \frac{2I}{I_{\text{max}}} \right) + 2n\pi. \]

To determine the value of \( n \) at a given voltage \( V \), one notes that retardation \( \phi \) and hence \( n \) is smallest at the largest \( V \). Thus, by referring to Fig. 6(a), we find, for example, that for \( 1.72 < V < 10 \), \( n \) has a value of 0, while for \( 1.16 < V < 1.72 \), \( n = 1 \), and so on.

To obtain the retardation \( \phi_0 \) at zero voltage, we note that \( I(0) = 3.0 \) V, while \( I_{\text{max}} = 10.8 \) V. There are a total of 3 oscillations, i.e. \( n=3 \) at \( V=0 \). Thus
\[ \phi_0 = \cos^{-1} \left( 1 - \frac{2 \times 3.0}{10.7} \right) + 2 \times 3\pi = 19.6. \]

From Eq. (10), the transmitted intensity \( I \) can be converted to retardation \( \phi \) and then plotted against voltage [Fig. 6(b)].

![Fig. 6. (a) Plot of experimentally measured transmitted intensity vs. V. (b) Plot of retardation \( \phi \) vs. V.](image)

From this plot, we can determine two important quantities of an LC retarder, i.e. its threshold voltage \( V_{\text{th}} \) and the half-voltage \( V_{\pi} \). \( V_{\text{th}} \) is the voltage at which the retardation starts to decrease (when the LC molecules start to align themselves with the applied electric field). \( V_{\pi} \) is the voltage at which there is a phase shift of \( \pi \) (antiphase). From Fig. 6(b), we obtain \( V_{\pi} = 2.3 \) V, and \( V_{\text{th}} = 0.45 \) V.
Method 2:

A cleaner method to determine the retardation $\phi$ is by placing a $\lambda/4$ waveplate at $45^\circ$ to the LC cell (as shown above). In this configuration, the LC cell acts as a voltage-modulated polarization rotator. A voltage of 2 V at 2kHz is applied on the LC cell and the analyzer axis is rotated. The axis orientation $\phi$ relative is recorded where maximum transmission occurs. This is repeated for an applied voltage range of $2 \text{V} < V < 10 \text{V}$, and the variation of $\phi$ plotted against $V$. The sample results are plotted in Fig. 8.

Analysis

The $\lambda/4$ plate converts the elliptically polarized light emerging out of the LC cell into a linearly-polarized one. The orientation of the plane of polarization $\phi$ w.r.t. to the $\lambda/4$ plate axis is proportional to the retardation $\phi$. Thus, the above graph has the same shape as the high voltage range of Fig. 6(b). In fact, $\phi = \phi/2$, as can be seen in the following Jones matrix analysis:

Let $\mathbf{u}_1$ be the Jones vector of light emerging from the LC. From earlier analysis, we have

$$
\mathbf{u}_1 = M_2(\phi) \cdot \mathbf{w}_1 = \frac{1}{2} \begin{pmatrix} 1 + e^{i\phi} & 1 - e^{i\phi} \\ 1 - e^{i\phi} & 1 + e^{i\phi} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 + e^{i\phi} \\ 1 - e^{i\phi} \end{pmatrix}
$$

$$
= \frac{e^{i\phi/2}}{2} \begin{pmatrix} e^{-i\phi/2} + e^{i\phi/2} \\ e^{-i\phi/2} - e^{i\phi/2} \end{pmatrix} \equiv \begin{pmatrix} \cos(\phi/2) \\ -i\sin(\phi/2) \end{pmatrix},
$$

after disregarding a phase factor. When $\mathbf{u}_1$ passes through the $\lambda/4$ plate (Jones matrix $\mathbf{Q}$), we have

$$
\mathbf{u}_2 = \mathbf{Q} \cdot \mathbf{u}_1 = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix} \begin{pmatrix} \cos(\phi/2) \\ -i\sin(\phi/2) \end{pmatrix} = \begin{pmatrix} \cos(\phi/2) \\ -\sin(\phi/2) \end{pmatrix},
$$

which is a linearly polarized light oriented at $\phi/2$ to the $x$-axis. This provides proof that the LC cell and $\lambda/4$ plate combination acts as a polarization rotator.
7. Determining the orientation of LC molecules

The aim of this section is to relate the experimentally measured retardation of light to the LC microscopic property (i.e. angular tilt $\psi$) of the LC molecules. The retardation is related to the anisotropy of the LC refractive, i.e.

$$\phi = \frac{2\pi(n(\psi)-n_o)d}{\lambda},$$  \hspace{1cm} (15)$$

where $d$ is the cell thickness, $n_o$ is the ordinary refractive index (experienced by light polarized along the LC cell fast axis), and $n(\psi)$ is the refractive index for polarization along the slow axis at tilt angle $\psi$. The tilt dependence of $n(\psi)$ is given by:

$$\frac{1}{n^2(\psi)} = \frac{\cos^2\psi}{n_e^2} + \frac{\sin^2\psi}{n_o^2},$$  \hspace{1cm} (16)$$

where $n_e$ is the extraordinary index of the LC material. From the LC cell specifications, we have $d = 8.38 \times 10^{-6}$ m, $n_o = 1.5103$ and $n_e = 1.7445$.

Note that at $V = 10$ V, the LC molecules are more or less fully aligned along the electric field, i.e. $\psi = 90^\circ$. The LC cell is thus optically inactive, with $n(\psi) = n_o$ and $\phi = 0$. In practice, however, we obtain some residual retardation $\phi_{\text{offset}}$ due to axis misalignment of optical components, etc. This offset has to be subtracted in order to obtain the actual retardation due to the birefringence of the LC material.

Inverting Eq. (16), we have

$$\phi = \cos^{-1} \left( \frac{1}{n^2(\psi)} - \frac{1}{n_o^2} \right),$$  \hspace{1cm} (17)$$

Thus, from Eqs. (15) and (17), we can use the data obtained in Section 6 to plot the angular tilt $\psi$ as a function of the applied voltage $V$ [Fig. 9(a)].

![Fig. 9. (a) Plot of tilt angle $\psi$ vs. $V$. Dotted line denotes experimental data, while solid line is the theoretical prediction. Linear plot obtained from (a) after some algebraic manipulation.](image)

The solid line in Fig. 9(a) from the theoretical expression relating $\psi$ to $V$, i.e. [5]
\[ \psi = \begin{cases} 0 & V < V_{th} \\ \pi/2 - 2\tan^{-1}\left[ \exp\left(-\frac{V-V_{th}}{V_0}\right) \right] & V > V_{th} \end{cases} \tag{18} \]

We can rearrange the above equation, so as to obtain a suitable linear curve to plot and determine the value of \( V_0 \), which is a measure of the “rigidity” of the LC molecules. From Eq. (18) above, we obtain

\[ V = V_{th} - V_0 \ln\left\{ \tan\left[ \frac{\pi}{2} \left( \frac{V}{V_{th}} - \psi \right) \right] \right\} = V_{th} - V_0 f(\psi) , \tag{19} \]

\( V \) is plotted against \( f(\psi) \) for the voltage range \( V_{th} < V < 2.0 \) [Fig. 9(b)], and \( V_0 \) determined from the gradient. It was found that \( V_0 = 0.994 \, V \).

8. Time response of LC molecules

In this section, we investigate a property of LC molecules which is a major shortcoming as far as dynamic (video) applications are concerned, i.e. their slow time response \( \tau \). For normal TN LCs, \( \tau \) are in the range of several milliseconds.

![Fig. 10](attachment:fig10.png)

**Method:**

We use the same set-up as Section 5, i.e. with the \( \lambda/4 \) plate removed. Next, using the controller software, such that an AC bias signal consisting of two amplitudes \( V_1 \) and \( V_2 \), is applied to the LC cell via the controller card. The larger amplitude \( V_1 \) corresponds to the final peak in the transmitted intensity \( I \) of Fig. 7 (~ 3V), while \( V_2 \) is set at a sub-threshold value of 0.5V. The time duration for both \( V_1 \) and \( V_2 \) is set at ~ 20 ms. The signal from the LC controller is fed into Channel 1, while the photodetector output to Channel 2 of the oscilloscope. Both channels are displayed simultaneously [Fig. 10(b)]. From the output profile, \( \tau_{on} \), the rise time to 90% of full brightness, and \( \tau_{off} \), the decay time from maximum to 10% of full brightness are obtained.

**Analysis**

From the sample output:

\[ \tau_{on} = -0.004042 \, (-0.01568) \, s = 11.64 \, ms \]
\[ \tau_{off} = 0.01677 - 0.007252 \, s = 9.52 \, ms \]
Theoretically, the rise time constant $\tau_{on}$ is dependent on several to the material properties of the LC material [6]

$$\tau_{on} = \frac{\gamma d^2}{k \pi^2} \left[ \left( \frac{V}{V_{th}} \right)^2 - 1 \right]^{-1}, \quad (20)$$

where $\gamma$ and $k$ are the rotational viscosity and elastic constants of the LC molecules. In addition, the threshold voltage $V_{th}$ is also related to the material properties as follows:

$$V_{th} = \frac{k \pi^2}{\Delta \varepsilon}, \quad (21)$$

where $\Delta \varepsilon$ is the anisotropy in permittivity.

$$\Delta \varepsilon = \Delta (n^2) = (n_2^2 - n_0^2) = (1.7445^2 - 1.5103^2) = 0.7623. \quad (22)$$

Substituting the numerical values into Eqs. (20) and (21), the rotational viscosity constant is found to be $\gamma = 2.00 \times 10^6 \text{ Nsm}^{-2}$.

9. Conclusions

On completion of the experiment, the student will gain experience in setting up an optical measurement system, and be familiar with various optical components and associated electronics to control/display the system inputs and outputs. A high degree of mathematical analysis of the experimental data is required. This ensures that students attain proficiency of the mathematical tools used in optics (principally that of Jones analysis), and thus gain rigorous understanding of the optical properties of LC material. Students will also discover the relationship between microscopic properties (molecular orientation, elastic forces) and macroscopic quantities (birefringence, time response). More importantly, they will learn that the LC optical properties can be systematically controlled by external biases. This external control forms the basis of LC application in displays and other devices.

10. Miscellaneous

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11. References


Undergraduate Elective on Optoelectronic Materials and Devices

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Abstract: An elective course on optoelectronic materials and devices offered at the University of San Diego is described. Main topics include band structure, semiconductor alloys, optical processes, photodetectors, light emitting diodes, laser diodes, fiber optics, and quantum wells. Laboratory projects and innovative pedagogical aspects of the course are also discussed.

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Introduction
From DVD players to fiber optic communication networks, optoelectronics are everywhere. To educate productive modern engineers, it is essential to introduce them to the important concepts underlying the multidisciplinary field of optoelectronics. The importance of this has been discussed for over a decade. In 1992 in a guest editorial, W. T. Cathey said "it seems inevitable that the key technologies for transmitting and perhaps processing information will be based on the manipulation of photons, rather than electrons." [1] Many excellent examples of optoelectronics education for undergraduates have been reported including for example those in a special issue of the IEEE Transactions on Education [2] on optoelectronics education and the previous Education and Training in Optics and Photonics (ETOP) conferences [3].

This paper discusses an elective course in Optoelectronic Materials and Devices which is being developed at the University of San Diego (USD) for juniors and seniors in electrical engineering. The course aims to provide an introduction to optoelectronic materials and devices and to aid the students' professional development by addressing issues such as the ability to critically evaluate technical papers, conduct effective literature research, and express information orally and in writing. Thus in addition to lecture and laboratory, several other opportunities were provided to directly address these professional development issues.

Course Structure
The elective course, EEE 194 Optoelectronic Materials and Devices, consists of three hours of lecture and three hours of laboratory per week. Due to the limited availability of laboratory facilities, the enrollment is capped at eight students. Typically there are about twenty students in junior and senior level required electrical engineering classes at USD. Students usually have a choice of two or three electives in a given semester. In Fall 1999 during its first offering, seven students including juniors and seniors took the course. In Fall 2001, five seniors took the course. This paper will focus on the 2003 offering. There was one midterm exam and a cumulative final exam. Before each exam, the instructor provided detailed objectives. On the syllabus, the overall course objectives were stated as

By the end of the course, students should be able to:
1. Describe, using band diagrams and appropriate equations, the physical operation of important optoelectronic devices including semiconductor lasers, light emitting diodes (LEDs), and photodetectors.
2. Identify key performance parameters of lasers, LEDs, and photodetectors and be able to calculate or design to achieve these parameters using appropriate data, information, and equations.
3. Explain the materials issues involved in the design of lasers, LEDs, and photodetectors.
4. Describe typical characterization techniques for optoelectronic materials and devices including equipment required, information obtained, and performance parameters.
5. Conduct laboratory experiments to characterize optoelectronic sources and detectors.
6. Identify at least 2 current topics in optoelectronics research.
7. Conduct effective literature research including critically evaluating technical papers, and expressing information orally and in writing.

Note that these objectives are also designed to satisfy ABET 2000’s criteria a through k.
Active learning was emphasized in this course beginning with the syllabus where the instructor explained that her class philosophy is based on research which has demonstrated that the best learning occurs when the learner is actively involved. Thus students are expected to come to class on time prepared to think, participate, and learn. Lecture notes are prepared using a word processor and distributed to the students. Typically some sections are left for students to fill in including answers to simple questions and working out of example problems. Students may be called upon individually to answer questions during lecture and usually work on problems in small groups. Throughout the lecture notes, attempts were made to appeal to different learning styles including having many figures for visual learners (see for example Figure 1), text for verbal learners, an organized outline for sequential learners, emphasis on motivation for global learners, applications for intuitive learners, specific examples for sensing learners, problem solving for active learners, and sufficient detail for future review for reflective learners [4].

![SPONTANEOUS EMISSION](image1)

![STIMULATED EMISSION](image2)

Fig. 1. Example of figure from lecture notes used in EEE 194 Optoelectronic Materials and Devices.

**Lecture Topics**

The topics explored in the course began with about three weeks on the fundamentals necessary to understand optoelectronic devices. Then each of the main optoelectronic devices was considered for about 2.5 weeks: photodetectors, light emitting diodes (LEDs), and laser diodes. The last two regular lectures focused on quantum wells. Optical communication was often used as an example of an application. The investigation of each optoelectronic device centered on its device physics, applications, and performance parameters. Emphasis was placed on choosing a specific device based on criteria such as wavelength of operation, cost, and performance. Discussions of the physical realizations of these devices were based on an understanding of crystal growth and device fabrication. One of the most difficult aspects of this course is the lack of a good textbook at the undergraduate level for currently changing topics such as white LEDs or vertical cavity surface emitting lasers (VCSELs). The required textbook was Singh’s Optoelectronic Materials and Devices [5]. However, articles from sources such as *Laser Focus World* and *IEEE Spectrum* as well as instructor handouts were used extensively.

Obtaining reference material at a level that is accessible to undergraduates is challenging but fun for the instructor.

Students at USD learn about basic semiconductor physics and the device physics of a pn junction/diode in their Engineering Materials Science class. Thus they need only a brief review of these topics. However, they also need to expand on these topics by considering 2-D band structure particularly as it relates to direct and indirect bandgap materials, semiconductor alloys particularly the importance of both lattice constant and bandgap, and high-field carrier motion including breakdown. Basic optical process (emission and absorption) are also new topics for them. A variety of processes are covered here including distinguishing between radiative and nonradiative emission, surface recombination, recombination lifetimes, quantifying absorption via an absorption coefficient, and bandedge, high energy, and low energy transitions. Students learn to distinguish between spontaneous and stimulated emission. (See Figure 1 for excerpt from lecture notes.)
In the photodetector section, the general operation of converting optical energy to electrical energy is stressed. Then students are introduced using band diagrams and appropriate equations, to the physical operation of photodetectors including photodiodes, photoconductors, pin diodes, avalanche photodiodes, and phototransistors. Advantages of each type are considered. Key performance parameters of photodetectors are identified such as responsivity, efficiency, and spectral response. The materials issues involved in the design of photodetectors are investigated. For example, given appropriate information, students must be able to choose a suitable material for a window layer for a heterojunction photodiode and explain the purpose of a window layer as well as describe the importance of a constant gain-bandwidth product for photodetectors. In addition during this section, some time is spent discussing important devices whose operation is related to that of photodetectors including solar cells and charge coupled devices (CCDs). Noise is also considered since it is important in characterizing detector performance.

Given recent advances in LEDs, many changes were made in the LED section between the course offerings in 1999 and 2003 particularly on white LEDs. This section begins with the physical operation of LEDs and identification of performance parameters of LEDs such as efficiency and spectral response including distinguishing between injection efficiency, recombination efficiency, and extraction efficiency. Ways to maximize efficiency are considered including designing epoxy domes. The impact of the human eye for visible wavelengths is discussed including why 1 mW of light at different wavelengths would appear to have different brightness to a human. Key materials issues involved in the design of LEDs are explored including using direct versus indirect bandgap materials and identifying materials used for red, blue, and infrared LEDs. The current technology and applications of white LEDs are investigated and compared with conventional lighting. Viewgraphs and articles from the Lumileds website were helpful in this section [6]. Having simple physical examples of white, blue, red, and infrared LEDs wired to 9-V batteries were excellent pedagogical tools. The section concluded with some examples of LED applications including optoisolators and LEDs designed for telecommunications.

Lasers are the last major optoelectronic devices considered and students are usually excited to learn about their operation and the conditions necessary to achieve lasing. Population inversion is defined and students learn to explain how it is achieved in a laser diode. Performance parameters of lasers are identified such as efficiency and spectral response. The key materials issues involved in the design of laser diodes are explored. Students calculate the longitudinal mode spacing (in nm or Hz) of a laser diode given the cavity length, operating wavelength, and refraction index of the material. They distinguish between optical and carrier confinement and explain how each is achieved in a laser diode. They learn to explain the concept of threshold for a laser and how to tell experimentally if a laser diode were operating above or below threshold and measure the threshold current. Several device designs that are used to lower threshold currents of laser diodes are considered. Distributed Bragg reflector (DBR) and distributed feedback (DFB) lasers are introduced. Students compare edge-emitting laser diodes and vertical cavity surface emitting laser diodes (VCSEL) including several advantages of each. Students learn to perform simple design calculations for DBR mirrors. Finally, a comparison between external and direct modulation for a laser diode is made.

The final topic in the course was an introduction to quantum wells. Quantum wells had already been mentioned in the discussion of laser diodes. Since undergraduates can easily become discouraged if presented with too many equations and may be intimidated by the words “quantum mechanics”, the initial focus is to have them explain what a quantum well is, cite at least two reasons why quantum wells are interesting, and briefly describe the information that a wavefunction provides. The derivation of a simple equation for energy levels in a quantum well based on Schrödinger equation enables them to be able to estimate the energy levels (in eV) of electrons or holes in a quantum well. The quantum confined stark effect (QCSE) in semiconductors and how it may be used in an electroabsorption modulator are also discussed.

Laboratory
The laboratory for this course was offered in the USD Optoelectronics Laboratory which has been supported by funding from the university as well as the National Science Foundation [7]. Facilities include two Newport optical tables, an Ocean Optics fiber-coupled spectrometer, a collection of optoelectronic positioners and mounts, the Newport Projects in Fiber Optics kit, an ILX Lightwave laser diode controller, an atomic force microscope, Newport optical power meters, electronic measuring equipment (multimeters, power supplies, pulse generators), and several computers with National Instruments LabVIEW hardware and software. Due to the expense of some of this equipment, having multiple stations is not possible. Since students learn better when they are active participants, most lab sessions included two groups of two students each and two lab exercises/stations. Thus it took two lab periods for the entire class to perform each experiment. Students wrote a formal group report following guidelines provided for most labs. For Experiments 4 and 7, individual reports specific to the experiment were required.
Table 1. Experiments performed in Optoelectronic Materials and Devices in Spring 2003

<table>
<thead>
<tr>
<th>Laboratory Number</th>
<th>Laboratory Title</th>
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<tbody>
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<tr>
<td>2</td>
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<td>Characterizing Sources of Light</td>
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<tr>
<td>7</td>
<td>Optical Communication Links</td>
</tr>
</tbody>
</table>

The titles of the labs are listed in Table 1. Each lab will be described briefly focusing on its objectives. In Lab 1, students performed four modules as an Introduction to Fiber Optics: speed of light [8], total internal reflection, wave guiding, and optical voice link [9]. Students also read an article on the evolution of fiber optic cables [10]. This introductory exercise was intended to enable the students to explain wave guiding, describe total internal reflection and its importance for fiber optics, experiment with a simple fiber optic system, and calculate the speed of light using experimental data.

Lab 2 continued the investigation of Fiber Optics by having students take measurements of the attenuation of plastic fiber at several wavelengths and examining the optical voice link in more detail. Specifically, they learned to use a fiber-coupled spectrometer to measure the peak wavelength of an LED, use an optical power meter to measure the optical power emitted by an LED, calculate the absorption of a material at a given wavelength based on experimental data, observe the signals on an oscilloscope for an optical transmitter and receiver for a variety of input signals, and describe the main different in output signal between a fluorescent and incandescent light source.

In Lab 3, Detectors of Light using transmission measurements, students analyzed the absorption properties of several samples including one of their own choosing that they brought to lab such as sunglasses or film. Students also compared the response times of different detectors including a phototransistor, photodarlington, photoconductor, and photodiode [11].

The fourth lab, Introduction to Microfabrication Laboratory was intended to help students gain an appreciation for the semiconductor fabrication process that is also used to fabricate optoelectronic devices. Semiconductor fabrication is not covered in any other required course in the curriculum at USD. Students watched videos about the general process of semiconductor fabrication from crystal growth to computer assembly, “Silicon Run” and “Silicon Run II” [12], as well as a brief promotional CD showing modern 300 mm manufacturing with its automation [13]. They read the first two chapters of Jaeger’s book on microelectronic fabrication [14]. The instructor also showed and discussed some physical examples including blank wafers, wafers with photoresist, fully processed wafers, bonded devices, layouts, and masks.

In one part of Lab 5, students coupled light from a HeNe laser into an optical fiber [15]. In the other part of Lab 5, they experimented with simple light and dark activated circuits, optoisolator circuits, and demonstrated their own night light. By the end of this lab, they were able to describe the issues involved in coupling light from a laser into an optical fiber, compare the response of circuits with photoconductors and phototransistors, and demonstrate the performance of an optoisolator. Although coupling light into a fiber is challenging and tedious, most students appreciated the opportunity to work with state of the art equipment.

In one part of Lab 6, Characterizing Sources of Light, students measured and compared optical power versus input electrical current (P-I curves) for a visible LED and a visible laser diode using LabVIEW. In the other part of Lab 6, students learned about different sources of light including white light sources (LED, W-Halogen), gas (HeNe) and diode lasers, and different color LEDs by comparing their emission spectra obtained using a fiber-coupled spectrometer.

In the last lab period, the students explored a fiber optic communication link and multiplexed two stereo signals. The sources of light were an LED and a laser diode and the analog modulation was provided by two tape players. Based on Project 8 of Newport’s Projects in Fiber Optics Kit [16], this experiment was unique in that two students from the French Military Academy at St. Cyr had prepared the experimental set-up as part of their senior thesis. The French students also prepared and delivered a presentation to the USD students describing the operation of the link, the problems they had encountered, and their experimental results. They demonstrated the multiplexing and then the USD students did some experimentation of their own as shown in Figure 2. Due to the large number of components and the need for multiple precise alignments, it is not practical to have students construct the link entirely on their
own in 1.5 hours. Having the link set up so that students see it working and then take some measurements allows them to focus on understanding rather than getting too frustrated by the alignments. The USD students were impressed with the French students’ skill at using PowerPoint to animate graphics in their description of the multiplexer and felt it enhanced their own understanding of the technical content. After their own attempts to align light to fibers, they were especially impressed with the French students’ experimental skill in assembling a complicated setup.

![Fig. 2. Students experimenting with the optical communication link (Lab 7).](image)

**Contemporary Issues in Optoelectronics**

Several innovative pedagogical techniques were integrated into the course. These brought contemporary optoelectronic issues into the classroom and allowed the students to develop some professional skills in research and communication. Engineers must demonstrate the ability to research a topic and communicate their findings orally and in writing. Thus, students were given the opportunity to explore an area more deeply by writing and presenting a paper on a topic of their choice. Topics ranged from organic LEDs to lasers in medicine to photonic crystals to free space communication systems. In the syllabus on the first day, the parameters of this project were described (presentation to class and report: 6-10 pages typed, cover sheet, appropriate documentation of multiple references). To enhance the quality of the final product in a busy semester, interim deadlines were provided. About four weeks into the class, students must submit a topic and state why they chose this topic, one thing they know about it, one thing they want to investigate, and give appropriate citations for at least 2 references. About four weeks later, they must submit an outline identifying the specific topics to be discussed. About three weeks later, a draft of the paper is due. It must be in the format of the final paper and is peer reviewed in class on the day it is submitted. Final papers are due two weeks later or about 1.5 weeks before the semester ends to allow time for the instructor to grade and return the papers on the last day of class. The final paper due date is also the first day of presentations. Each student presents for about 30 minutes including questions so two students present per class period. About one month before the end of the semester, students sign up for a presentation date and a consultation with the instructor a few days before their presentation date. Students peer review each other’s presentation and the instructor provided a summary for each student including comments from peers and instructor and grades for content and presentation from peers and instructor. Most students did very well on the presentation with grades ranging from 75 to 100%. The grading by the instructor and the students was quite consistent always being within 4% of each other. All students used PowerPoint. Some students included demonstrations, mini-lectures on the board, candy rewards, or interactive questions. Each presenter also prepared two questions with answers based on their presentation for possible use on the final exam. They were encouraged to share these with their classmates either during or after their presentation. After some editing by the instructor, a short question based on each presentation was included on the final exam.
In Spring 2003, the last fifteen minutes of each Friday class was devoted to “Fabulous Friday” where one student led a discussion of a recent article which he/she had distributed to the class on Monday. The leader prepared a summary of the article and several questions for the class. Articles came from sources such as *Laser Focus World* and *IEEE Spectrum*. This endeavor gave the students an opportunity to develop oral communication skills and the ability to critically evaluate new information from sources other than textbooks and lectures. Topics included applications of LEDs for curing blindness, iris scanning for security, and thin-film photovoltaics. Some students used their Fabulous Friday topic as their paper topic. Some did outside research to enhance their discussions. Throughout the course of the semester, articles had been tending to get shorter until one very short one proved difficult to understand due to the lack of details provided. The class recognized this and discussed the criteria for a suitable article. Students enjoyed the range of topics. Leading a discussion was challenging for many including the instructor as she strives to balance her own participation, providing context or background, and letting the students lead.

Contemporary issues in optoelectronics were also incorporated into several homework assignments. For example, one homework assignment required students to evaluate an issue of *Laser Focus World*. They reviewed the "Back to Basics" article in their issue and identified the section that they found most interesting. Investigating the advertisements helped them learn about the diversity of current products and companies that make up the modern optoelectronic industry. It also forced them to look at a magazine that they might have initially found intimidating and helped to build up some confidence in their own ability to learn from such sources. In April 2003, the class visited the Navy’s SPAWAR Systems Center and toured the electronic fabrication facilities as well as the labs in the Photonics and RF Branch. They learned about topics such as Bragg gratings, optical filtering, and fused fiber coupling and had the opportunity to talk with researchers about their careers.

**Student Response**

Student response to the class was quite enthusiastic as may be expected for a small elective course. Although students worked hard, they believed they learned a lot which made it worthwhile. At the end of the semester, students filled out separate evaluations for the lecture and laboratory. Each evaluation consisted of responding on a scantron to specific questions as well as written comments. The choices for student ratings were “Excellent, Very Good, Good, Fair, Poor, and Very Poor”. All responses on both evaluations were Excellent, Very Good, or Good corresponding to median numerical ratings from 4.0 to 4.9. In the lecture, the highest ratings were reported (4.9, 88% Excellent, 12% Very Good) for “instructor’s contribution to the course,” “instructor’s effectiveness in teaching the subject matter,” “use of class time,” and “course organization”. The lowest rated category (4.0, 38% Excellent, 25% Very Good, 38% Good) was “reasonableness of assigned work”. In the laboratory, the highest rated category (4.9, 88% Excellent, 12% Good) was “instructor’s ability to deal with student difficulties.” The lowest rated category (4.1, 25% Excellent, 62% Very Good, 12% Good) was “content of the lab section”. Given the nature of optoelectronic equipment, it is important that the instructor and students be flexible and adapt if things do not go as planned.

On the end of the semester evaluations for the lecture, all students reported that the class was intellectually challenging. The aspects of the class that they reported contributed most to their learning were the class handouts (5), active learning (3), labs (2), and Fabulous Fridays (2). Another student stated, “The focus on concepts with just enough math and lots of application was great. I didn’t seem to get lost in the numbers.” Several students commented that the book was too “intimidating” and could be improved. Four students said they had no suggestions for improving the class, one asked for more specifics on Fabulous Fridays, another for more emphasis on devices to balance out the materials section, another thought the paper and presentation were too heavily weighted (30% of class grade).

In the end of the semester evaluations for the laboratory, all students again reported that the lab was intellectually challenging. Responses to the aspect of this class that contributed most to learning included

- Open discussion labs and availability of extra help
- Lab write-ups because you have to think about the results you obtained to analyze them
- Being able to work in teams of two. Having lab every other week.
- The experiments were interesting and complimented the lecture material.
- Small class size and great lab equipment was a huge bonus. The field trip and presentations were beneficial.

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• Discussing the problems experienced in lab with lab instructor. This gave me a better understanding of the material covered in class and made me see some connections to real world applications.
• The class was well organized and spent the right amount of time on detectors and emitters. It was difficult to find time to work on the papers, so the numerous assignments for the paper really helped.

For aspects of the class that detracted from learning, 5 students said nothing. One wanted more lab time, another thought the paper was weighted too heavily and there was confusion about Fabulous Friday expectations, the third cited problems with a specific experiment that made analysis frustrating. For suggestions to improve the lab, five students indicated “nothing”. One wished lecture were more like Fabulous Friday, another suggested a small experimental project at the end of the semester, and the third said “The lab portion was excellent. The only thing I wish we would have done was to build our own optical communication system, like the French students did.”

An informal midcourse evaluation was also conducted. Based on some excellent suggestions, changes were made to the instructions on Fabulous Friday to include more details on the type of article that would be suitable (length, related to a topic discussed in class) and the requirements for the summary. Students were generally happy with the pace and structure of the course. Some wanted more examples and an effort was made to address this in subsequent lectures.

Summary
An undergraduate elective course on optoelectronic materials and devices is being developed at the University of San Diego. Lecture topics include semiconductor fundamentals as well as essential optoelectronic devices: LEDs, lasers, and photodetectors. Students performed seven laboratory experiments, chose a topic related to optoelectronics, wrote a paper, and delivered a presentation to the class. Further opportunities to explore current topics and improve presentation skills were provided in homework assignments and “Fabulous Friday” discussions. Student response to the class as demonstrated by course evaluations was very positive indicating that they found it challenging but worthwhile.

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Method to make accurate measurements of refractive index

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We propose in this work the use a diffraction grating to calculate the wavelength inside a transparent material of parallel plane faces, with the purpose of measuring the magnitude of their refractive index. The errors of this method and the precision are discussed.

Keywords: metrology, diffraction grating, refractive index.

1. Introduction

One of the important parameters used in optics is the refractive index. There are different methods to measure the refractive index in the visible region. One of the techniques used to carry out these measurements uses the method of minimum deviation that suffers a ray of light when crossing a prism\(^{(1)}\). Other common methods are based on the determination of the critical angle and in the Brewster angle\(^{(2)}\). A method of determination of the refractive index using prisms was described recently by Hsiu\(^{(3)}\). In the method of Hsiu, the incident beam is normal to the first surface of the prism the refraction is manifested only in the second surface. The relationship obtained under this configuration is

\[
\alpha + \delta = \alpha \sin \alpha,
\]

where \(\alpha\) the angle of the prism and \(\delta\) the deviation angle that suffers the beam in the second surface. The method of Hsiu can be used to determine refractive index of lens doing some modifications. Most of these methods are based on the application of the refraction law. The method that we propose in this paper considers the diffraction of the light.

2. Theory

The diffraction grating is normally used for measuring wavelength through the grating equation

\[
a \sin \theta_m = m\lambda
\]  

\(1\)
for the case when the incident plane wavefronts of light make an angle of $0^\circ$ with the plane of the grating, $m$ is order of interference. The zero-order principal maximum provides no information about the wavelength of the illumination. Information about the wavelength of the illuminating light can only be obtained by measuring the angular position of the higher-order principal maximum. We will employ this method for measuring wavelength inside of a optic glass. It is known that a wave inside a transparent material changes its space period in the form

$$\lambda' = \frac{\lambda}{n},$$

(2)

this result is used to measure $n$ measuring the wavelength $\lambda'$ inside the material and using $\lambda$ of a well-known source. Considering the Ec.(1) the separation $dy$ of two diffraction orders is

$$dy = \lambda \frac{s}{a},$$

(3)

where $s$ is the distance from the grating to observation screen, $a$ is the separation of slits. If the same experiment is realized inside a material with $n$ index, then the wavelength change by

$$\lambda' = \frac{dy'}{s}a,$$

(4)

Finally using the Ec. (1) we can obtain $n$ calculating $\frac{\lambda}{\lambda'}$; where $\lambda$ is the wavelength in the vacuum of a well-known source, $\lambda'$ is the wavelength inside the material. Substituting the Ec. (4) and Ec. (5) into the Ec. (2) that $n = \frac{\lambda}{\lambda'}$ can be obtained by

$$n = \frac{dy}{dy'},$$

(5)

where $dy$ and $dy'$ are the separation of diffraction orders when the experiment is realized in the vacuum and inside a material, respectively.

2. Experimental procedure

The experimental setup consist of a He-Ne laser of 3 mW and 632.8 nm and optical glass cube as material under test. The cube is mounted on a XY positioning stage platform. The parameter $a$ of the diffraction grating used is 6.81 microns. The measurements of $dy$ and $dy'$ was carry out with a CCD camera. The measurements was doing placing the diffraction grating close to the DA face of the cube see Fig.1, measuring the separation $dy'$ among -1 and +1 diffracted orders in the opposite face CD of the cube. Subsequently we measure $dy$ among the same orders but now outside of the
cube. The pattern of diffraction inside the cube is observed in the CB face and outside in the BF face, see Fig. 1.

To observe the diffraction grating we put a diffuser sheet in the CB face of the cube. To observe the diffraction pattern inside and outside of the cube this was translated laterally in the Y direction. The measurements was realize with a CCD camera with a zoom lens. The Fig. 2 show the diffraction patterns obtained.
Results

Using the images of Fig. 2 we obtained the value of $dy'$ and $dy$ of 190.1 and 289 pixels, respectively. Giving the magnitude of 1.521 for the refractive index. The value specified of $n$ is 1.52504 for the He-Ne laser. Our result obtained has a precision of 0.2 %.

Conclusions

We used a diffraction experiment to calculate the refractive index of a glass cube. This method is simple and has good precision. This experiment can be use to show in the classroom in an elementary optics course the effect of how the wavelength change inside the materials. The method gives as an alternative technique of easy implementation in ours optics laboratories.

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References


FOURIER TRANSFORMS IN CLASSICAL OPTICS
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ABSTRACT
The principle of superposition plays critical roles in both classical and quantum physics. This paper will underscore the conceptual continuities and divergences in the process of successfully using Fourier transforms as a classical superposition tool to quantify Fraunhofer diffractions, far-field space and temporal coherence, Fourier transform spectroscopy and dispersive broadening of a short pulse.

INTRODUCTION
In physics, the principle of superposition in a linear domain and the Fourier mathematics have become synonymous by virtue of their great success in explaining old physics, predicting new physics and paving the way for a wide variety of technological break through (practical instrumentation). This article will focus on application of Fourier transform (& series) in Optics and establish a conceptual continuity between the various phenomena that successfully use Fourier math.

1. FRAUNHOFER DIFFRACTION

This is one of the earliest example of identifying a mathematical representation of a physical phenomena based on a physical hypothesis to facilitate the understanding of the optical diffraction phenomenon. Huygens-Fresnel principle (or, HF integral) treats wave propagation as a superposition of secondary, spherical wavelets emanating out of every point on the wave front. This integral transforms into a superposition of plane waves in the far-field. Then the far-field integral resembles exactly like the Fourier transform integral of the near field illumination. This has given birth to the field of Fourier Optics for image processing. The detectable spatial energy distribution continuously evolves as the wave front propagates.


Every point on a wave front emits a new spherical wavelet, the “forward direction being normal to the original wave front point. The resulted new wave front due to propagation is the superposition of all the HF wavelet amplitudes at the target plane. In the case of our incoherent extended source, one only sums the intensities due to HF wavelets from every point of the incoherent source (Fig.1). A spherical wavelet originating at O, has the phase delay (in radian) on the (one dimensional) X-plane given by \((2\pi\lambda)/(x^2/2r)\). The exponential representation is \(\exp(+ikx^2/2r)\) (+ sign convention for the point of divergence on the left).
Figure 1. Heuristic derivation of Far-field diffraction pattern using simple geometrical and physical optics.

Figure 2. A spherical wave front, at small angle approximation, gives a phase front \( \exp(+ikx^2/2r) \) on the planar X-axis.

Figure 3. A lens introduces a phase factor \( \exp(-ikx^2/2f) \). This causes a plane wave to converge at its back focal plane.
\[
x^2 + f^2 = (f + \delta f)^2 = f^2 + \delta f^2 + 2f \delta f \approx f^2 + 2f \delta f \text{ (neglecting small } \delta f^2) \quad (1)
\]

Or, \( \delta f = (x^2/2f) \) \( (2) \)

**A lens creates a Fourier transform in its focal plane:**

We want to find out the complex amplitude \( U(x) \) on the x-plane (back focal plane) when an object \( U(\xi) \) is illuminated by a uniform, continuous wave (CW), monochromatic (single carrier frequency), plane wave at the front focal plane (\( \xi \)-plane). We will use the concepts of ray optics, wave optics, and Huygens-Fresnel principle along with the built-in principle of linear (amplitude) superposition of coherent waves.

Consider a general point, \( \xi \), on the \( \xi \)-plane. It emanates a spherical HF wavelet & arrives at the lens- (\( \alpha \)-) plane with a curvature \( \exp[+ik\alpha^2/2f] \). This quadratic curvature gets flattened by the reverse quadratic phase factor of the lens \( \exp[-ik\alpha^2/2f] \) and a plane wavelet emanates toward the focal plane. The plane wavelet intersects the x-plane at an angle \( \theta = \sin^{-1}(\delta/x) \approx \tan^{-1}(\delta/f) \), where \( \delta \) is the relative delay of the plane wavelet at the x-point on the X-plane and \( \theta \) is a small angle. So, the path delay is, \( \delta = \xi x/f \). Or, the titled plane wave representation is \( \exp[ik\xi x/f] \).

If the complex amplitude at the point of origin of the HF wavelet at the \( \xi \)-point is \( U_\xi(\xi) \), then the complex amplitude at the x point is \( CU_\xi(\xi)\exp[ik\xi x/f] \), where \( C \) is a propagation constant including amplitude reduction due to spherical divergence.

The total contribution of complex amplitude at the x point, \( U_x(x) \), is the linear superposition (sum, or integral) of all the contributing points from the \( \xi \)-plane, so the integration should cover the entire “open aperture”:

\[
U_x(x) = C \int U_\xi(\xi) \exp[ik\xi x/f] \, d\xi \quad (3)
\]

Or, \( U_x(x) = C' \int U_\xi(\xi') \exp[2\pi i\xi' x] \, d\xi' \quad (4)\)

Where we have substituted \( \xi' = \xi/f \). This last integral equation is the mathematical definition of the Fourier transform relation between \( U_x(x) \) and \( U_\xi(\xi') \).

Although the above derivation is carried out heuristically, without going through the rigorous (Raylength-Sommerfeld or other similar) formulation, it preserves all the fundamental concepts accurately except some constants that give the exact numerical value for the complex amplitude. The key point to note here is that the exponential factor within the integral looks like the mathematical Fourier transform kernel. Thus the far-field diffraction pattern is the Fourier transform of the diffracting aperture function. This fortunate mathematical coincidence paved the way for the development of a major field, optical signal processing, where Fourier mathematics and related theorems serve as major mathematical tools. One should note two important points here:
(i) First, the appearance of the Fourier transform-like structure of the Eqns. 2 & 3 is an evolutionary consequence of the physical hypothesis (Huygens-Fresnel Principle) that a propagating wave front can be represented as a superposition of an infinite number of spherical wavelets.

(ii) Second, the Eqns. 3 & 4 represent real physical propagation of light waves from one physical plane to another, allowing us the opportunity for optical signal processing by real physical manipulation of the diffracting wave fronts with different physical apertures.

1.2 Rigorous Diffraction Theory.
The rigorous Rayleigh-Sommerfeld formulation of diffraction theory based on Huygens-Fresnel principle is given by the Eq.1 [Goodman, Eq.4-8]:

\[ U(P_0) = (1/i\lambda) \int U(P_1) [\exp(ikr_{01})/r_{01}] \cos ds \]  \hspace{1cm} (5)

For a rectangular diffracting aperture, the far-field (or, Fraunhofer) diffraction pattern, with small angle approximation, the Eq.1 simplifies into a summation (integral) of plane waves:

\[ U(x,y) = \exp(ikz). \exp{(k(x^2+y^2)/2z)/iz\lambda} \int U(\xi, \eta) \exp{-2\pi i (x\xi + y\eta)/\lambda z} d\xi d\eta \]  \hspace{1cm} (6)

For conceptual simplicity, let us consider the one dimensional case of an infinitely long diffracting slit. Ignoring some constants and phase factors outside the integral, and after substituting \((\xi/\lambda z) = \xi'\), one can write:

\[ U(x) = C'' \int U(\xi') \exp{-2\pi i x \xi'} \ d\xi' \]  \hspace{1cm} (7)

The Eqns. (3), (4) and (6), (7) are equivalent.

2. Fourier Transform Spectroscopy: When radiated electromagnetic field (EMF) is split into two beams and is superposed again with a relative delay between them, one can record the detectable energy as sinusoidally varying intensity fringes, which we call interferograms. The spatial variation of these periodic fringes is exactly related to the carrier frequency of the EMF. When one has many such CW carrier frequencies, each frequency forms its own periodic fringes, because interferogram materials do not record time varying mutual interference between different carrier frequencies. It only records the time averaged, self-interference (light beams of different frequencies do not interfere with each other). The resultant interferogram now has a variable visibility function, multiplied by an average cosine oscillatory component. Fourier mathematics also uses sinusoidal functions in its transformational relation. Thus, the oscillatory part of the interferogram can be “Fourier transformed” to extract the spectral energy distribution of the original complex EMF. This is at the foundation of the successful field of Fourier transform spectroscopy applied in understanding fundamental physics and chemistry of atoms and molecules. Thos field was
developed by A. Michelson in late 1800’s, which earned him a Nobel Prize, the first for a US physicist.

When a collimated monochromatic wave (CW or continuous wave carrying single frequency) passes through a Michelson interferometer with an asymmetric beam splitter (not a 50/50 one), the superposed amplitudes on the beam splitter can be represented by,

\[ E_r(t, v_0, \tau) = A_1 \cos(2\pi v_0 t - \phi_1) + A_2 \cos(2\pi v_0 t - \phi_2), \]  

(8)

Figure 3. ………………………

\( E_r \) indicates real representation of E-field, instead of complex representation, used later. The relative phase delay between the two wave front is \( \phi_2 - \phi_1 \), \( \tau \) being the relative time delay (total path delay \( \delta \) divided by \( c \)). We cannot detect the amplitude of light. We can only infer the presence of light by carefully observing light induced changes in material properties as it absorbs energy from the electromagnetic field. The light induced reaction (photo-chemical, photo-electric or photo-conductive), I, is proportional to time average of the square of the light amplitude [Klein]:

\[ I_d(v_0, \tau) = \frac{1}{T} \int_{t} E_r^2(t, v_0, \tau) \, dt \approx I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos 2\pi v_0 \tau = I_0 + I_0 x \cos 2\pi v_0 \tau, \]  

(9)

where, \( I_0 = (I_1 + I_2) \), and \( x = 2 \sqrt{I_1 I_2} / (I_1 + I_2) \),

(10)

and, \( I_{osc} = I_0 \cos 2\pi v_0 \tau = I_0 \cos 2\pi m. \)  

(11)

In the last step, we have used the order of interference, \( m = (\delta/\lambda) = v_0 \tau \). This \( m \) is a very important parameter in all interferometry. In the linear domain, the source frequency remains unaltered, or a constant, so the location of the repeated, fringes for the same source frequency, is determined by \( \tau \), given by \( m = v_0 \tau \). So, the variable component of the recorded fringe, \( I_0 \cos 2\pi v_0 \tau \), that is of importance for us. If \( v_0 \) is unknown, and the unequal beam amplitude factor, \( x \) is fixed for a given beam splitter, then by counting the fringe (\( m \)) with measured value of \( \tau \), will give us the value of the carrier frequency, \( v_0 \), if the beam is monochromatic. But, we have a very complex interpretational problem if \( x \) is a variable and, especially, if it varies with time, either due to changing reflectivity of the beam splitter with time, or due to amplitude variation of the incident beam with time as produced by the source.

Let us consider the case of a time varying amplitude, or a pulsed source. Let us assume that we have cut out a Gaussian pulse from the above single frequency, CW laser, oscillating with a frequency, \( v_0 \). It actually could be a quite long pulse of width \( \delta t \), as long as the moving
mirror of the Michelson interferometer can be moved by $\tau > \delta t$. Now, we have a situation even when the beam splitter is a 50/50 divider, instead of $x$ being unity, it still remains as an unequal beam amplitude factor, $x(t)$. Now the fringe visibility varies with time due to the unequal amplitudes incident on the beam splitter (and the detector) at different times, except when the delay, $\tau$, between the two mirror paths is exactly zero. By repeating the experiment with the same pulse but with varying values of the delay, $\tau$, we can obtain the variation of the fringe visibility with delay, as shown below. For each experiment with one pulse, one must integrate the interference signal for the entire duration of the two pulses (replicated, delayed and superposed by the Michelson interferometer). Note that we have only one source frequency, but a changing fringe visibility with $\tau$. One can mathematically show that the Fourier transform of the fringe visibility function (conjugate variables, $v_\ell$ and $\tau$) is equal to the normalized, square modulus of the Fourier transform of the pulse amplitude function, $a(v_0, t)$ (conjugate variables being $v_\ell$ and $\tau$). This is also called the Wiener-Khintchine theorem or the autocorrelation theorem [Klein]. We will come to it later again. We are underscoring the suffix of $v_\ell$ as it represents mathematical variable “Fourier frequencies”, in contrast to the frequency of the electric vector originating at the emitting source. Our point is that turning on a simple mechanical shutter to create amplitude pulse from a CW, monochromatic source, does not create any new electric vector frequencies. This is a linear process. The fringe visibility varies for a pulsed light because of superposition of unequal amplitudes, and not due to new optical spectrum.

![Delayed pulse pairs](image1)

**Figure 4.** Variation of long-time integrated, fringe visibility in a simple Michelson interferometer as the delay between the mirrors are varied.

The situation is even more complex when the incident beam contains many unknown carrier (or source) frequencies. Let us now consider the case of a CW beam with two carrier
frequencies, \(v_1\) and \(v_2\), and the narrow reflectivity coatings of the beam splitter gives different values for the unequal beam amplitude factor \(x\) as \(x_1\) and \(x_2\). Under this situation, Eq.(11) can be re-written as:

\[
I_{osc} = I_{01} x_1 \cos 2\pi v_1 \tau + I_{02} x_2 \cos 2\pi v_2 \tau
\]  

(12)

There is a very simple and yet profoundly important, and experimentally validated assumption buried in Eq.(12), that different optical frequencies do not interfere with each other, as long as we use slow detector. Cross terms between different source frequencies have been dropped for slow detectors (see last section on beat and mode locking). If we use a 50/50 beam splitter, the situation is a bit simpler with \(x_1 = x_2 = 1\), and one gets:

\[
I_{osc} = I_{01}(v_1) \cos 2\pi v_1 \tau + I_{02}(v_2) \cos 2\pi v_2 \tau
\]  

(13)

If our goal is to determine the source frequencies, \(v_1\) and \(v_2\), we are still stuck with two more unknowns, \(I_{01}\) and \(I_{02}\). If these are equal, and let us normalize them, to unity, then we have:

\[
I_{osc} = \cos 2\pi v_1 \tau + \cos 2\pi v_2 \tau = 2 \cos 2\pi v_s \tau \cos 2\pi v_d \tau
\]  

(14)

Where, \(v_s = (v_1 + v_2)/2\) \(v_d = (v_1 - v_2)/2\), are the mean of the sum and the mean of the difference of the two source frequencies. Thus, Eq.(14) describes the modulation of high frequency spatial fringes (\(m_{1,2} = v_{1,2} \tau\)) with a low frequency factor \(v_d = (v_1 - v_2)/2\), also known as waxing and waning of fringe visibility. In early times, people used this technique to determine \((v_1 - v_2)\) of some atomic spectra, like Sodium fin structure doublet, known as D\(_1\) and D\(_2\) spectral lines. After the inventions of lasers and holography, people are innovating various techniques by exploiting this repeated oscillation of fringe visibility as a tool to accurately measure the depth and shape of complex 3D objects, etc. Eq.(14) can be generalized for the case of continuously distributed frequencies:

\[
I_{osc} = \int I(v) \cos 2\pi v \tau \, dv
\]  

(15)

The Fourier transformed, mathematical inversion relation is then given by [see Klein]:

\[
I(v) = \int I_{osc}(\tau) \cos 2\pi \mu \tau \, d\tau
\]  

(16)

As in Eqns (3), (4) or (6), (7) where the diffraction equations naturally evolves into a form that becomes identifiable with Fourier transform, here also the oscillatory part of an interferogram takes the form of a simple cosine Fourier transform. Just as in case of diffraction, the Fourier transform conjugate variables (\(\xi-x\)) for space-space diffractive propagation, are real and based on validated Physics hypothesis (HF Principle), here also the conjugate variables (\(v-\tau\)) are physically measurable quantities. However, the common root of identity of the mathematical expression of a physical phenomenon with a mathematical theorem arises from the linearity and the use of sinusoidal function as the basis. Electromagnetic field follows sinusoidal oscillation, and the basis function for Fourier transform theorem is also sinusoidal function. However, the Eq.(15) must still be used with great caution. First, it sums fringe intensities, and not field amplitudes, and ignores cross
products between various source frequencies. However, as mentioned before, this is a valid assumption for slow, time averaging light detectors. Second, we have dropped $x(v,t)$ in Eq.(15) based on the assumption that all the source frequencies have sustained, CW amplitudes of $V(v)$. If the atoms and molecules literally emit packets of spreading (according to HF Principle), classical light pulses, each carrying unique source frequencies, given by the quantum condition $\Delta E_{q} = h \nu_{q}$, then Michelson’s spectroscopy should be generalized using Eq.8 instead of Eq.(11), with the added attention that the superposed amplitudes are functions of time. This is the model that is illustrated in Fig.4. If the incident pulse is $a(t)\exp[i2\pi v_{0}t]$, then the complex version of Eq.(8) is given by:

$$E_{c}(t,v_{0},\tau) = a(t)\exp[i2\pi v_{0}t] + a(t-\tau)\exp[i2\pi v_{0}(t-\tau)]$$  \hspace{1cm} (17)$$

Fast photo-induced energy exchange is equally well given by a time average integral of $E_{r}^{2}$, as in Eq.(9) when the E-field is represented by real function, or simply by $(E_{c}E_{c}^{*})$, when $E_{c}$ is complex. As illustrated in Fig.4, the recorded fringe intensity needs a second time integration to cover the entire duration of the pair of pulses:

$$I_{d}(v_{0},\tau) = \int E_{c}(t,v_{0},\tau) E_{c}^{*}(t,v_{0},\tau) \, dt$$  \hspace{1cm} (18)$$

After substitution of Eq.(17) in Eq.(18) and a series of simplification, one can obtain the oscillatory component of the fringe variation as:

$$I_{osc}(v_{0},\tau) = \gamma(\tau) \cos(2\pi v_{0}\tau)$$  \hspace{1cm} (19)$$

Eq.(19) is good for single frequency, single pulse. This is the parallel of Eq.(11) for a single frequency, CW source. The function $\gamma(\tau)$ is the normalized auto correlation of the pulse $a(t)$. The time integrated, oscillatory fringe for a Doppler broadened, thermal discharge lamp with atomic emitter can now be modeled as:

$$I_{Dop. osc}(\tau) = \int I_{osc}(v,\tau) \, dv = \int \gamma(\tau) \cos2\pi v \tau \, dv$$  \hspace{1cm} (20)$$

One can compare this with the Eq.(15) for the CW case. The RHS of Eq.(20) represents the mathematical Fourier transform of the autocorrelation function. By the autocorrelation, or Wiener-Kintchine theorem,

$$S_{f}(v) = \int \gamma(\tau) \cos2\pi v \tau \, dv$$  \hspace{1cm} (21)$$

Here $S_{f}(v)$ is the normalized, square modulus of the original pulse, $a(t)$. Now, the Eqns.(20) and (21), implies that the oscillatory interferogram, $I_{Dop. osc}(\tau)$, is equivalent to the mathematical spectral density function, $S_{f}(v)$.

3. BEAT SPECTROSCOPY AND MODE LOCKING

In the above two examples of experimental success, the energy of the EMF is recorded over a time as an average of the square of the instantaneous amplitudes. Along with the hypothesis
that in the time averaged recording, there is no interference between different frequencies. But, both beat spectroscopy and mode locking generate time varying energy “re-distribution” of superposed EMF of different frequencies. Then how does one reconcile the observational success of the time average recording of the first two phenomena (Far-field diffraction & FT spectroscopy)? We have recently published a paper [Optics Express 11 (8), p.944, (2003)] that helps one to understand the conceptual continuity between all these phenomenon by simply accepting the hypothesis that the principle of superposition is manifest only in interacting materials, dictated by their quantum properties; EMF’s do not operate on (or, change) each other. They simply pass through each other. The detailed discussions and experimental validations are presented in the above paper.

4. ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge useful discussions with colleagues Masahiro Oikawa, Vladimir Serikov and Shigeo Kittaka of NSG Corporation. Some of the computations presented in the figures here, were computed by David Young and DongIk Lee.

5. REFERENCES

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Creating the Future: 
Towards an Integrated System for Photonics 
Education and Training 

(Invited Paper)

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Abstract: A critical factor for realizing the steady and sustainable growth of the optics industry in Singapore is an adequate and steady supply of qualified personnel at all levels. In this paper, the formation of the National Alliance for Photonics Education and Training (NAPET) is reported. The main goal of NAPET is to develop an integrated system for photonics education and training in Singapore. The important role of global networking and cooperation will also be discussed.

1. Introduction

In recognizing the growth potential of the global market in optics and photonics Singapore is determined to accelerate the growth of the optics industry. A critical factor for realizing the steady and sustainable growth of the optics industry is an adequate and steady supply of qualified personnel at all levels. To fulfill this need, the National Alliance for Photonics Education and Training (NAPET) of Singapore was formed in March 2003.

In this paper, we will first review the key events in the development of photonics in Singapore in the past 10 years and the current state of photonics education and training in Singapore. The formation of NAPET, its mission and plan of activities will be elucidated. In particular, it is emphasized that a key factor in determining the success of NAPET is to further develop and strengthen our collaboration with other research centers and organizations, both locally and internationally, because it will facilitate the sharing of resources and experiences. Accordingly, the role of NAPET in the proposed Global Photonics Education Network (GPEN) will be discussed.

2. Development of Photonics in Singapore

Development of photonics in Singapore had been lagging behind as compared to the more well-developed countries. Nevertheless, in the past ten years, the pace of development has quickened, notably through a series of key events as summarized in Table 1. I have been privileged to have the opportunity to play a key role in these events as noted in the table, in the brackets under the name of each event. Through all these endeavors we have established close relationships with the optics communities in Singapore as well as a global network for international cooperation. In particular, they have culminated to the formation of the National Alliance for Photonics Education and Training (NAPET) in March 2003, as elucidated in the next section.

3. Development of an Integrated System for Photonics Education and Training

In this section, before the discussion on the formation and mission of NAPET, we will first provide an overview on the current state of photonics education and training in Singapore. It is pointed out that due to the highly competitive, structured, and standards-based curricula for the primary schools, secondary schools, and junior colleges, education in photonics has mainly be provided through project-based learning and to a selected group of students. To provide the learning opportunities for students at all levels an integrated education and training system consisting of a variety of innovative, flexible programs must be developed. These programs should also be designed to prepare the students for greater success in higher education and career development.

The design and implementation of the photonic education and training programs for students must build on the strong science and mathematics foundation that has been the hallmark of the Singapore education system. It must
also capitalize on the schools’ excellent infrastructures, especially the information technology and education resources. Furthermore, with the multi-disciplinary nature of photonics the new curricula could be incorporated to physics, chemistry, and biology subjects. The wide range of applications of photonics would also provide the students an excellent opportunity to learn the principles and practice of engineering. This will not only enrich the students’ learning experience, but will also prepare them for advancement to a professional career through tertiary education. The formation of NAPET has enabled the whole optics and photonics community to work together to achieving these goals.

3.1 Current State of Photonics Education and Training in Singapore [1]

(1) Project-Based Learning
In the past four decades Singapore has established an education system that serves well the developments of the major industry clusters, including semiconductor, electronics, and petrochemicals. In Fig. 1, an overview of the Singapore education system from Primary to University Education is shown. Within this system, curricula of primary, secondary, and junior college education have been highly competitive, structured, and standards-based [2]. As a consequence, coverage on optics has been limited to simple geometrical and physical optics. It has been difficult to incorporate modern optics and photonics into the formal curricula. Accordingly, project-based learning is one of the effective ways for cultivating the interest of students in optics and photonics, both at the secondary and postsecondary levels. At the senior secondary and junior college (grades 9 to 12) level, the various mentoring schemes have been very successful. In these schemes, faculty members from universities and polytechnics serve as mentors for research projects during school vacation periods. Students are required to submit a technical report and make an oral presentation at the end of the project. With the establishment of the Photonics Exploration Lab at the Raffles Institution and the Photonics Learning and Research Centre at The Chinese High School in 2000, students has been able to engage in project-based learning during term times as well.

At the polytechnics and universities, students have been involved in optics- and photonics-related projects during the In-House Practical Training (IHPT) period, the Industrial Attachment (IA) period, and in their final year of study. For the IHPT, students work for up to 8 weeks in the laboratories on campus under the supervision of academic staff. During the industrial attachment period students work full time at private companies, research institutes/centers, or government labs for up to 6 months. On the other hand, the final year projects cover the whole final year of study, with many projects sponsored by industry. Therefore, these projects provide excellent opportunities for students to immerse in the academic and industrial research and development environments.

(2) Special Training Programs
To accelerate the pace of manpower development for the industry, the Singapore Economic Development Board (EDB) [3] has been working with the tertiary institutions on several special manpower programs. Under these programs, companies co-sponsor trainees for specialization in a certain area of photonics, and the trainees are required to work with the companies upon completion of the training. In addition, EDB also offers other programs, including the Training and Attachment Program (TAP), the Research and Training Program (RTP), and the Postgraduate Manpower Program (PMP). Specifically, TAP provides assistance to private companies for training their staff in new areas such as optical networking; RTP recruits and places qualified trainees in local research institutes/centers or government labs for up to 6 months. On the other hand, the final year projects cover the whole final year of study, with many projects sponsored by industry. Therefore, these projects provide excellent opportunities for students to immerse in the academic and industrial research and development environments.

(3) Formal Education Programs
The development of formal curricula at the polytechnics and universities has also been intensified in the past few years. At the technician and technologist level, the four polytechnics are offering elective subjects or modules, covering lasers, optoelectronics, fiber optics communications, and optical networking. At the undergraduate level, NUS offers electives in machine vision, modern optics, optoelectronics, and optical communications, as well as a minor on optics in information technology. On the other hand, NTU launched a Final Year Specialization program in photonics in July 2000, offering final year students a range of subjects including laser engineering, fiber optics communications, optoelectronics, optical system and instrumentation, photonic instrumentation design, and photonic system design. Now going into its fourth year, this program has been very well received.
At the graduate studies level, the number of masters and Ph.D. students has been increasing in recent years. The areas of research include lasers, optoelectronics, fiber optics, fiber optic communications, fiber optics sensors, biomedical imaging and instrumentation, optical signal processing, optical storage, and displays.

3.2 Mission of the National Alliance for Photonics Education and Training (NAPET)

The conception for the formation of the National Alliance for Photonics Education and Training (NAPET) was first revealed at the Forum on Education and Training in Optics and Photonics held on 2 December 1999 in Singapore. The idea was further developed through the following years [1,4-6], and has culminated to the actual formation of NAPET at its inaugural meeting held on 29 March 2003 at the Singapore Economic Development Board [7].

NAPET is a national alliance of high schools, technical training institutes, tertiary institutions, research institutes, the industry, government bodies, and professional societies. The mission of NAPET is to establish Singapore as a centre of excellence for education and training in optics and photonics, through the development of an integrated education and training system that is vital for the continual development of workforce and sustainable growth of the photonics industry in Singapore. To realize this mission, the objectives of this alliance are formulated as follows:

- To identify the needs for manpower education and workforce development in optics and photonics;
- To develop comprehensive, structured programs for education and training of researchers and scientists;
- To develop comprehensive, structured programs for education and training of technicians and technologists;
- To develop outreach programs for students, parents, teachers, school counselors, and the public;
- To develop continuing education and training programs and workshops for teachers, counselors, parents, working professionals, administrative personnel, policy makers, and the public;
- To assess, implement, evaluate, and improve these programs.

To achieve these objectives appropriate committees and working groups will be formed. Programs developed and experience gained elsewhere are valuable resources and references for developing our own programs. More importantly, the dedication and collaboration of the whole optics community in Singapore are critical for the success of this endeavor. In the following, we will focus our discussion on the development of the following programs:

- **Education programs** for high schools, institutes of technical education, and tertiary institutions
- **Training programs** for teachers, technicians, engineers, and administrators
- **Outreach programs** for students, parents, teachers, counselors, administrators, policy makers, and the general public

Currently, there is an urgent need for the development of training programs for the industry and outreach programs to promote the awareness and understanding of photonics for students and the public. In the education system, as described in the previous section, photonics education has mainly been concentrated at the senior undergraduate and postgraduate levels, and specialized training programs in the polytechnics. At the high school level, education in photonics has been facilitated through project-based learning. To provide the learning opportunities for students at all levels an integrated education and training system must be developed. In particular, there is an urgent need for the development of photonics curricula for high school and technical training institute students. The formation of NAPET has enabled the whole optics and photonics community to work together to achieving these goals.

To expedite the development of photonics education and training programs at the high school and technical institute levels, teachers training workshops will be organized. Through these workshops, working groups for curriculum developments will be formed. Academic staff from universities and polytechnics, as well as research scientists and engineers from the industry and research institutes will play important roles for the organization of the workshops.

To facilitate the development of relevant programs for the photonics industry, NAPET will conduct a survey on the training needs of the industry and the expertise residing in the education institutions and research institutes. This survey is the first step towards the creation of a database that could be used for matching industry needs to the pool of expertise, thereby enabling more efficient and effective development of training programs.

Over the past ten years, we have established a global network with a wide range of organizations and institutions. The formation of NAPET will further enhance and expand this network that will provide invaluable experience and resources for the development of the education and training programs in Singapore. More details are provided in the next section.
4. Collaboration with Other Organizations and Institutions

As stated before, one of the key factors for our success is the collaboration with other organizations and institutions. Accordingly, in this section we will provide a brief account on the potential collaborators, both local and international.

4.1 Collaborators in Singapore

Within the Nanyang Technological University (NTU) and the National Institute of Education (NIE) [7] there are many academic groups and research or technology centers that could be our collaborators. Some of them are more closely related to our work as listed below:

- Centre for Educational Development (CED), NTU
- Centre for Continuing Education (CCE), NTU
- Centre for Research on Small Enterprise Development (CRSED), NTU
- Office of Professional Attachment (OPA), NTU
- Instructional Science Group, NIE
- Science and Technology Education Group, NIE
- Natural Sciences Group, NIE
- e-Learning Competency Centre (ECC), NIE

Outside of the campus, we could also collaborate with many organizations, including the Ministry of Education (MOE), Ministry of Manpower (MOM), members of the Singapore Centre of Photonics Excellence (SCOPE) [3], and professional societies as listed below:

Members of SCOPE (besides NTU)
- National University of Singapore (NUS)
- Economic Development Board (EDB)
- PSB Corporation
- Singapore Institute of Manufacturing Technology (SIMTech)
- Data Storage Institute (DSI)
- Institute of Microelectronics (IME)
- Institute for Materials Research and Engineering (IMRE)

Professional Societies:
- SPIE Singapore Chapter
- IEEE Singapore Section
- Institute of Physics, Singapore (IPS)
- Institute of Engineers, Singapore (IES)

4.2 International Collaborators

As stated before, over the past ten years we have established a global network with a wide range of organizations and institutions. They include: the various optics clusters in the Asia-Pacific region, Europe and North America; the international professional societies; and organizations that provide photonics and engineering education materials. The support and collaboration of this network will be a key factor for the success of NAPET. In particular, we will actively participate in the development of the Global Photonics Education Network (GPEN) proposed recently. As a national body, NAPET will be one of the national nodes within this education network.

5. Concluding Remarks

The development of an integrated education and training system in optics and photonics is vital to the continual development of the workforce and the sustainable growth of the photonics industry in Singapore. In particular, the development of new, innovative photonics education and training programs will also enrich science education in the schools in Singapore. The formation of NAPET has enabled the whole optics community to work together to
achieving these goals. The collaboration with local and international organizations will be a key factor to ensuring the success in this endeavor.

6. References

[8] Nanyang Technological University (NTU) website: http://www.ntu.edu.sg
### Table 1
**Key Events in the Development of Photonics in Singapore**

[1994-2003]

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Organizations/Institutions Involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Photonics Research Group formed [Founding Member]</td>
<td>School of EEE, NTU</td>
</tr>
<tr>
<td>1995</td>
<td>SPIE Singapore Chapter formed [Founding Chair]</td>
<td>SPIE members in NTU, NUS, other institutions, and the industry</td>
</tr>
<tr>
<td>1998</td>
<td>Inauguration of Singapore Optics/Photonics Forum</td>
<td>Organized by PSB and SPIE Singapore Chapter</td>
</tr>
<tr>
<td></td>
<td>UNIDO-ICS Training Course on Photonics Technology for the 21st Century: Principles and Applications [Coordinator, Chair of Organizing Committee, and an Instructor]</td>
<td>School of EEE, NTU; United Nations Industrial Development Office (UNIDO); and International Centre for Science and High Technology (ICS)</td>
</tr>
<tr>
<td>1999</td>
<td>Forum on Education and Training in Optics and Photonics (ETOP) [Organizer and Speaker]</td>
<td>School of EEE, NTU; SPIE Singapore Chapter; EDB; PSB; other education institutions; and industry</td>
</tr>
<tr>
<td></td>
<td>The International Symposium on Photonics and Applications (ISPA ‘99) [Co-Chair, Organizing Committee]</td>
<td>Organized by School of EEE, NTU, SPIE, and SPIE Singapore Chapter</td>
</tr>
<tr>
<td>2000</td>
<td>Photonics Learning &amp; Research Centre established [Advisor]</td>
<td>The Chinese High School</td>
</tr>
<tr>
<td></td>
<td>Photonics Exploratory Lab established [Founding Member]</td>
<td>Raffles Institution</td>
</tr>
<tr>
<td></td>
<td>Singapore Centre of Photonics Excellence (SCOPE) formed</td>
<td>EDB, PSB, NSTB, NTU, NUS, Gintic, DSI, IME, IMRE</td>
</tr>
<tr>
<td></td>
<td>Photonics Association (Singapore) [PA(S)] officially formed [Founding Member; Chair, Education Committee]</td>
<td>Optics and photonics companies, Ngee Ann Polytechnics, and SPIE Singapore Chapter</td>
</tr>
<tr>
<td></td>
<td>ETOP 2001: The 7th International Conference on Education and Training in Optics and Photonics [Conference Chair; Chair of Local Organizing Committee]</td>
<td>Organized by School of EEE, NTU, SPIE, and SPIE Singapore Chapter</td>
</tr>
<tr>
<td></td>
<td>ISPA 2001: The 2nd International Symposium on Photonics and Applications</td>
<td>Organized by School of EEE, NTU, SPIE, and SPIE Singapore Chapter</td>
</tr>
<tr>
<td>2002</td>
<td>5th Singapore Optics/Photonics Forum &amp; Photonics World 2002 [Member, Organizing Committee]</td>
<td>Organized by PA(S) and HQ Link Pte. Ltd</td>
</tr>
<tr>
<td>2003</td>
<td>National Alliance for Photonics Education and Training (NAPET) formed [Founder and Chair, Coordination Committee]</td>
<td>An alliance of all education institutions, government bodies, professional societies, and the industry</td>
</tr>
<tr>
<td></td>
<td>Singapore-Australia Photonics School [General Chair, Local Organizing Committee]</td>
<td>Organized by School of EEE, NTU, PA(S), NAPET, and Australian Photonics Cooperative Research Centre (CRC)</td>
</tr>
</tbody>
</table>
Figure 1  Flowchart of the Singapore education system [2]
Evolution of a class in fiber-optic communications

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ABSTRACT:
Classes in fiber-optic communications, presented at Arizona State University (ASU) for four decades, have evolved in both content and delivery. Content updates followed the development of new components and network strategies, while delivery methods changed from blackboard-to-television-to-Internet. Evolution, evaluation, and future direction of these classes are described.

1. Introduction

A two-semester sequence in fiber optic communications has been offered at Arizona State University by the author since 1979. The first course has been offered almost every fall semester since then and the advanced course has been offered many times as a spring course. The first course is taught at the senior/first-year-graduate level and the second course at the first-year-graduate level. There is a laboratory for undergraduate students for the first course. The courses generally follow a textbook written by the present author and first published in 1984. The course content, the textbook, and delivery procedures have evolved over the past 24 years.

It is not surprising that course materials in technical subjects change. Fiber optics is a good example of this. At the time of the first presentation of the course in 1979, fiber communications was in its infancy. Since then advancements have appeared at a rapid pace. Numerous improvements and application evolved over the years. The fundamentals did not vary from what was known in the 1970s, but new components, new network strategies, and new applications became available every year necessitating changes in the course content and in the textbook. Unrelated to course content and textbook upgrades was a series of changes in the course delivery format.

The course content, textbook, and delivery evolution described for the fiber course parallels that of many other university science classes developed and presented over the last 25 years.

2. Course Content

Table 1 indicates some of the changes that have occurred since the first low-loss fiber was developed in 1970. The first column in the table describes the property of interest and the following four columns describe the change with time in that property. As an example, some of the first systems operated with carrier wavelengths near 820 nm, used multimode fibers having losses of 3 dB/km, ran at a rate of 45 Mb/s over 10 km
paths, and used time-division multiplexing. Skipping to the present decade, we have systems operating in the long-wavelength region (1260-1675 nm) with fiber losses of 0.2 dB/km and running at rates of 40 Gb/s. The fibers are single-mode, non-zero dispersion shifted fibers to improve bandwidth. The systems are dense-wavelength-division multiplexing allowing for numerous 40 Gb/s channels along a single fiber. With amplifiers (EDFAs or Raman), the system lengths are as long as needed over terrestrial and oceanic paths.

Advances in fiber technology produced systems capable of transmitting at ever increasing rates and longer distances. In addition, price reductions and component simplifications made fiber optics a candidate for lower-cost, low-rate, short-distance applications (such as LANs) as well.

Table 1 indicates fiber improvements over time. Most of the earlier components and systems remain viable. The newer developments have just added to fiber capabilities.

The lectures were easily updated on a yearly basis by incorporating new material as it became available. New developments could be mentioned in class almost as soon as they were announced in journals or at conferences. However the fundamentals of propagation in fibers, light generation (chiefly laser diodes and light-emitting diodes), and photodetection (PIN and avalanche photodiodes) did not change substantially. These fundamentals have always been the core of the course.

3. Course Textbook

The course followed the authors textbook fairly closely. The textbook was first published in 1984. Before it became available, the course was taught from notes that later became part of the textbook. The problem with textbooks in technical areas is the speed with which they become outdated. It the case of fiber-optic communications it is not a case of material becoming obsolete. It is more a case of new material becoming available. The new subjects were added in a second edition in 1988, a third edition in 1992, and a fourth edition in 1998. A fifth edition is in preparation. Even with this fairly aggressive publishing schedule, the book remains slightly behind the technology.

The textbook has always contained a bibliography of useful fiber books. The number of books in the bibliography, tabulated in Table 2, reflect the growing interest in optical communications over the period covered.

Another change has been the retail cost of the course textbook. It was first published (1984) as a paperback and sold for $14. The fourth edition (1998), in hardback, was recently priced at $80. Translations have been published in Japanese, Korean, and Persian. A separately published international version in English has accompanied each new US edition.

4. Course Delivery

The course delivery format has undergone a number of significant changes. They are listed in Table 3 and are the major motivation for this paper. The first change, from a lecture hall with a blackboard to one with a whiteboard, was fairly modest but much appreciated. Although about twenty years have passed since I last used chalk, I can still feel the extreme drying of the skin produced by its contact with my fingers.
The next change was more significant. Television studios were constructed and a network was assembled for delivering graduate-level classes to local companies. At its peak, more than 25 companies had receiving facilities. They included several sites for Motorola, Honeywell, and Intel, and single sites for Boeing, Lockheed, Litton, Phillips, VLSI, AG Communications, and others in the greater Phoenix area. On-campus students attended the live lectures as they were being televised. Students at the remote sites could watch the live lectures at their company locations and call in questions over telephone lines. Videotapes of the lectures were placed on file in the library. A number of students chose to view the videotapes rather than attend classes. Additionally, we observed that the remote students did not watch the television broadcasts as they were transmitted, but recorded the lectures and watched them at times of their own convenience.

Student response to the televised lectures was quite positive. No exhaustive assessment was done (it should have been done), but the regular instructor evaluations showed very strong acceptance of the televised lecture system. I believe the reason was the good quality of the transmission, its reliability, and the great convenience afforded to the remote student. Driving to school from the workplace, parking, walking to class, attending the lecture, and then reversing the process would have been much too time consuming.

Faculty participation in the television presentation was almost never a big issue. The instructor could give a lecture while writing on a chalkboard or on a paper pad or could lecture from prepared slides (and in the 1990s from PowerPoint slides). Homework and exams were delivered by a university courier. Company-employed proctors at the sites monitored exams. There was no additional faculty compensation for presenting televised classes.

In the 1990s the fiber course began being offered through the National Technological University (NTU). Students from all over the country attended the fiber class. The televised class was delivered by satellite to the NTU facilities. NTU distributed the video to its students. Basically, NTU students viewed videotapes of the class lectures. The NTU students were a few days to a week or so behind the live class because of delays in delivering the videotapes. NTU pays the instructor a nominal amount for each enrolled student. Student response was positive. Again, the quality of service and the convenience factor were probably the most important factors in student acceptance of the NTU remote delivery system.

The next variation to the course, begun in the 1990s, was the introduction of simulations to the lectures. This was made possible as there was a PC in the television studio and its screen could be recorded and televised. A number of computer simulations of fiber optic phenomena were prepared and integrated into the lectures. Examples simulations are on wave travel and ray propagation through a GRIN fiber. These simulations were the subject of a previous ETOP presentation. They are available for viewing at the authors web site. This addition to the class is listed as a PC enhancement in Table 3.

In the late 1990s the Internet was becoming pervasive. All students had Internet access either in their own homes or at campus computing sites. Because of this, course materials were made available exclusively on the Web. Blackboard (a popular commercial e-learning tool used to manage Web courses) was used. Materials posted included the lecture schedule, exam schedule, homework assignments, course
announcements, grading policy, posted student grades, laboratory schedule, laboratory manual, simulations, links to relevant Internet sites (e.g., fiber companies), and teaching assistant and instructor access information. The Web site was used by all course participants: on-campus students, local-television students, and NTU students. This use of the Internet is sometimes referred to as an Internet enhanced course.

It was decided to offer the first fiber course entirely over the Internet for the Fall 2000 semester. One of the motivations was the ASU participation in the Arizona Tri-University Master of Engineering program. This program combines courses taken at Northern Arizona University, the University of Arizona, and ASU. Classes taught over the Internet make them more accessible to students in the program than on-campus classes. Rather than an Internet-enhanced course, we are now talking about a true Internet course available in its entirety over the Internet.

Again, Blackboard was used for the course shell. It was decided to pre-record the lectures using a system call Tegrity WebLearner. At the time of the recording (summer 2000), we had no way of posting lectures presented in the TV studios directly onto the Web. Pre-recording has a number of advantages and disadvantages. One advantage is that lectures can be generic, without reference to the date given. Live lectures usually give cues as to when the lectures occurred. For example, the instructor may state that a homework set is due the next session. Without these cues, pre-recorded lectures can be used again other semesters. In fact, the pre-recorded lectures were used for a total of three successive Fall presentations of the first fiber class. Pre-recording frees the instructor from preparing and presenting live lectures. The disadvantage is that it is difficult to modify the class to add the latest changes in the technology. At the time of the digital recordings for the Internet, the course was simultaneously videotaped. All students had the option of watching the recorded videotapes in the TV studio at the assigned class time, watching the video tapes at a time of their choosing by checking them out from the library, or watching the lectures on the Internet. The videotaped lectures were transmitted for the local television and NTU students.

Tests were done in class for on-campus students. Exams for remote students were monitored by proctors.

Later, NTU gave its students the option of watching the lectures over videotapes or over the Internet. For these students the Internet removed the time-delay experienced in waiting for delivery of videotapes.

An extensive assessment of Internet delivery of the first course was made. The published results were generally favorable. A few on-campus students missed the direct contact with the lecturer. The convenience of being able to view the lectures at a place and time of their own choosing was the leading reason the students gave for approving the Internet format.

The second fiber course was also pre-recorded. This time RealPresenter was used for the recordings. The course was given on the Internet in Spring 2002.

In the latest incarnation of the first course (in Fall 2003) lectures are video streamed from the TV studios. On-campus students attend the live lectures. Online students can watch the lectures live on the Internet or can watch them at a later time. The lectures are typically archived and available on the Internet a few hours after the actual presentation. Students not enrolled for the Internet version of the course cannot view the lectures but can access all other material on the class Blackboard web site. There is an extra fee for
the Internet class. Video transmission and videotapes are no longer being provided. All distance learning is being done over the Internet. NTU has also migrated to Web-based classes. The faculty are compensated for the production and delivery of Internet classes.

Streaming video solves the problem of updating the class and the perceived problem of direct student-instructor contact for on-campus students. Assessment of this latest strategy will be performed at a later time.

5. Discussion

A lot has happened in the fiber communication industry since its inception in the 1970s. The fiber-optic communications courses at ASU have followed the progress of the technology. In addition, the course presentation has evolved as educational technology itself has progressed. Although fiber communications is now embedded in the world’s communications structure, the field slowed considerably in the years 2002 and 2003. Employment is significantly down from earlier times. Industry layoffs have been extensive. A popular technical journal, *Lightwave*, reduced the number of printed pages from 210 in its October 2001 issue to 54 in its February 2003 issue. This is another indication of the decline in the fiber industry. It is not clear whether or not the robust nature of the field will return. The need to train large numbers of engineers in this area needs to be evaluated.

Internet courses may become universally accepted as being equivalent to, or better than, conventional face-to-face classes. In this occurs, then further refinements can be envisioned. Several possibilities come to mind.

One example would be to make the courses truly asynchronous. That is, make the course independent of the familiar semester system. With pre-recorded lectures, a student could start the course at any time. The course could be refreshed each time it was taught live.

As another example, it is possible for schools to sell its recorded courses as complete packages to other schools that might be interested in offering them to their own students. This might, or might not, be acceptable practice but it is technologically feasible.

Recorded courses can also be repurposed for use in short courses, non-degree courses, audit courses, and certificate courses.

All these possibilities are being considered for the fiber-optics communications course described in this paper.

References

Table 1. Course Content Timeline.

<table>
<thead>
<tr>
<th></th>
<th>1970s</th>
<th></th>
<th></th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>820 nm</td>
<td>1310 nm</td>
<td>1550 nm</td>
<td>1260-1675 nm</td>
</tr>
<tr>
<td>Fiber loss</td>
<td>3 dB/km</td>
<td>0.5 dB/km</td>
<td>0.2 dB/km</td>
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</tr>
<tr>
<td>Fiber type</td>
<td>Multimode</td>
<td>Single mode</td>
<td>DSF</td>
<td>NZ-DSP</td>
</tr>
<tr>
<td>Light source</td>
<td>LED, LD</td>
<td>DFB LD</td>
<td>VCSEL</td>
<td>Raman lasers</td>
</tr>
<tr>
<td>TDM data rate</td>
<td>45 Mb/s</td>
<td>2.5 Gb/s</td>
<td>10 Gb/s</td>
<td>40 Gb/s</td>
</tr>
<tr>
<td>Distance</td>
<td>10 km</td>
<td>100 km</td>
<td>10,000 km</td>
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</tr>
<tr>
<td>Optical amplifier</td>
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<td>SOA</td>
<td>EDFA</td>
<td>Raman</td>
</tr>
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<td>Modulation</td>
<td>Current</td>
<td>Electrooptic</td>
<td>Electroabsorption</td>
<td></td>
</tr>
<tr>
<td>Modulator</td>
<td>Internal</td>
<td>External</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiplexing</td>
<td>TDM</td>
<td>WDM</td>
<td>DWDM</td>
<td>OTDM</td>
</tr>
<tr>
<td>Fiber data rate</td>
<td>45 Mb/s</td>
<td>25 Gb/s</td>
<td>1 Tb/s</td>
<td>5 Tb/s</td>
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<td>Connectors</td>
<td>SMA</td>
<td>ST</td>
<td>SC</td>
<td>SFF</td>
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<tr>
<td>Splices</td>
<td>Mechanical</td>
<td>Fusion</td>
<td>Quick splice</td>
<td></td>
</tr>
</tbody>
</table>

Key: DSF, dispersion shifted fiber; NZ-DSF, non-zero dispersion shifted fiber; LED, light-emitting diode; LD, laser diode; DFB, distributed feedback; VCSEL, vertical-cavity surface-emitting laser; SOA, semiconductor optical amplifier; EDFA, erbium-doped fiber amplifier; TDM, time-division multiplexing; WDM, wavelength-division multiplexing; DWDM, dense wavelength-division multiplexing; OTDM, optical time-division multiplexing; SMA, ST, SC, different style connectors; SFF, small form factor.

Table 2. Number of Textbooks in Bibliography of Textbook.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tr>
<td>Books</td>
<td>40</td>
<td>70</td>
<td>109</td>
<td>178</td>
<td>210</td>
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Table 3. Course Presentation Timeline.

<table>
<thead>
<tr>
<th>Time</th>
<th>Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>Chalkboard</td>
</tr>
<tr>
<td></td>
<td>Whiteboard</td>
</tr>
<tr>
<td></td>
<td>Local TV</td>
</tr>
<tr>
<td></td>
<td>National TV (NTU)</td>
</tr>
<tr>
<td></td>
<td>PC enhancements</td>
</tr>
<tr>
<td></td>
<td>Internet enhancements</td>
</tr>
<tr>
<td></td>
<td>Internet: Pre-recorded</td>
</tr>
<tr>
<td></td>
<td>Internet: NTU</td>
</tr>
<tr>
<td>2003</td>
<td>Internet: Streaming video</td>
</tr>
</tbody>
</table>
A needs assessment for a graduate level course in optical networking

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Abstract: To explore the need for a graduate level engineering course in optical networking, a needs assessment consisting of (i) an investigation of 14 existing optical networking courses, (ii) an analysis of online surveys among the networking community and the ASU electrical engineering department, (iii) faculty interviews, and (iv) focus groups was conducted. Survey responses from a total of 61 respondents were received and analyzed. The results support the need for a graduate level course in optical networking. Our analyses indicate that a graduate course in optical networking should (i) focus on the basic mechanisms and current trends in optical networking, (ii) be based on a text book and instructor slides combined with collections of examples and problems. Regarding the optimal delivery method it was found that current students and faculty strongly prefer face-to-face delivery complemented by on-line readings and assignments, whereas working engineering professionals are more open to the idea of online courses.

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1. Definition and Purpose

New bandwidth intensive telecommunications services, such as multimedia streaming entertainment, distance education, and telemedicine, require increased capacities in the Internet. It is widely believed in the networking engineering community that only fiber optics will be able to provide the enormous bandwidth required for future telecommunications services. For this reason, optical networking has been intensively explored in the networking research community over the past two decades and continues to be the focus of intense research efforts [1]. The outcomes of these research efforts are presented at the major networking conferences, such as IEEE Infocom, IEEE Globecom, and the IEEE International Conference on Communications in specialized optical networking sessions and workshops, which are very popular. In fact, for the past three years, the optical networking workshop being held during the IEEE International Conference on Communications has attracted the largest registration number among the ICC workshops [2]. In addition, specialized optical communications and networking conferences have enjoyed large attendance over the past several years, with the largest conference, the Optical Fiber Conference attracting over 10,000 researchers and engineers every year. Furthermore, recent years have seen the emergence of specialized optical networking journals and magazines, such as the Optical Networking Magazine, which was launched by Kluwer Academic Publishers in 1999, and the increasing number of networking articles in the IEEE/OSA Journal of Lightwave Technology. These extensive research and publication efforts indicate that optical networking is establishing itself as an important sub-discipline of networking.

Reflecting this trend, many electrical engineering graduate programs in the U.S have begun to offer courses on optical networking. However, in numerous institutions optical networking courses are not included in the core graduate engineering curriculum. As part of the effort to develop and expand the electrical engineering (EE) program at Arizona State University (ASU), it is needed to gain an insight into the need of a graduate course in optical networking at ASU, and what the optimal instructional contents, and optimal delivery method of the course would be.

To address this question, a needs assessment was conducted. A secondary goal was to investigate the attitudes of the broad engineering community (students, faculty, and engineering professionals) toward a graduate level optical networking course in general. The needs assessment was designed to answer the following questions: 1. Is it necessary to offer a graduate course in optical networking in the electrical engineering department at ASU? 2. What are the general attitudes of students, faculty, and engineering professionals toward a graduate optical networking
What would be the optimal instructional content, teaching materials, and delivery method for a graduate optical networking course?

2. Method

The methods and techniques in this needs assessment followed Rossett’s [3] suggestions for conducting a needs assessment. A comprehensive approach involving a combination of methods was employed. The following section provides the description of the various data sources, numerous data collection instruments, and the needs assessment participants.

3. Data sources and Instruments

3.1 Extant data

Extant data were obtained from optical networking and fiber optics graduate courses across the country. To get a nationwide picture of the optical networking field, syllabi and course descriptions for optical networking and fiber optics courses offered at other universities, mostly top EE graduate schools or equivalents to ASU were reviewed to identify the course goals, learning objectives, and contents. The syllabi and course descriptions were obtained from Columbia University, Northwestern University, University of Texas at Arlington, San Jose State University, University of Maryland, Virginia Tech, Massachusetts Institute of Technology, University of Hawaii, University of California at Davis, University of Pennsylvania, University of Arizona, Carnegie Mellon, Purdue University, and Iowa State University.

Based on the analysis of the obtained graduate optical networking and fiber optics curricula, syllabi, and course descriptions, a set of common learning goals and major content areas were identified. In addition, specific topics and research areas were extracted from the extant data. From this extant data analysis we created a list of the major optical networking and fiber optics topics that are being taught at the graduate engineering level. We compiled a set of questions to be used in an online survey to be distributed to the general engineering community. The initial set of questions (topic areas) was further clarified and refined as a result of interviews with experts from the optical networking and fiber optics field.

3.2 Online survey

The online survey was designed to determine the general perception of the importance of optical networking in the graduate engineering curriculum and the optimal content, delivery method, and teaching materials for a graduate optical networking course. The survey was distributed through the IEEE Technical Committee on Computer Communications (TCCC) mailing list, which reaches close to one thousand networking engineering professionals, students, and researchers across the U.S, and the mailing list of the electrical engineering department at ASU. The survey employed a four-point Likert type rating scale with the strongly agree category equaling a numerical value of 3 and strongly disagree equaling a numerical value of 0 in ranking the agreement with the individual statements. The survey required the respondents to rank (strongly agree, agree, disagree, strongly disagree) thirty-nine statements that covered the issues of the optimal (1) prerequisite knowledge that students should have before taking a graduate level optical networking course, (2) general focus areas of an optical networking course, (3) topics in Architectures and Hardware, (4) topics in Protocols, (5) topics in General Principles, (6) teaching materials and strategies, (7) course delivery method, and (8) the necessity of optical networking in graduate engineering curriculum in general. The respondents also indicated their current position as either a graduate student, faculty or engineering professional. The respondents were given the opportunity to provide additional comments and elaborations of their answers (rankings). These elaborations were considered as qualitative data source. The outline of the survey is enclosed in the Appendix.

3.3 Interview

Interviews were conducted with two faculty members (the chair of the graduate program and an assistant professor who is conducting research in optical networking) in the EE department at ASU. The goal was to explore the attitudes of a sample of the members of the EE department toward an optical networking graduate course. Specifically, questions targeted the perceived need for and students’ interest in a graduate optical networking course, the available support (physical, personnel, and educational resources) for implementing a graduate optical
networking course, and the perceived importance of a graduate course in optical networking for the general goals of the EE department at ASU. The interview encompassed role-specific questions such as “How would the optical networking course fit in the current EE graduate curriculum?” for the chair of the graduate program, and “What would be the focus of a graduate course in optical networking if you were to teach it?” for the assistant professor. Each of the interviewees responded to a set of ten questions. The approximate duration of each of the interviews was 45 minutes.

3.4 Focus group

A focus group was conducted with a sample of graduate students in the EE department at ASU. The purpose of the focus group was to determine students’ attitudes toward the potential course in optical networking, their perspectives on the optimal contents, instructional methods, and methods of delivery. The focus group participants responded to eight questions covering their knowledge of and interest in optical networking, the preferred course content, and delivery method. The questions were role-specific, such as “Are you taking or planning to take a graduate optical networking course? Explain why?”. The focus group discussion lasted approximately 1.5 hours and the obtained qualitative data provided more in-depth insights into the role of optical networking in the graduate engineering curriculum.

4. Participants

A total of sixty-one responses were received from the online survey. The entire nationwide sample consisted of twenty faculty members, thirty-five graduate students, and six engineering professionals. The survey was distributed over the IEEE TCCC mailing list and over the ASU EE mailing list. The aim was to reach the broad networking engineering community (faculty, graduate students, engineering professionals) as well as the specific ASU EE community. The survey did not require biographical information except for the respondent’s current occupation. Approximately one half of the online survey responses were obtained from the ASU respondents. This constitutes approximately 52% of the gross sixty-one responses nationwide.

A total of thirty-two respondents from the EE department at ASU participated in the online survey that was distributed through the ASU EE mailing list. Specifically, six EE faculty members (approximately 18% of all ASU survey response rate) responded to the online survey. Twenty-five ASU EE graduate students responded to the online survey, counting approximately 78% of the overall ASU survey response rate. In addition, one ASU respondent was an engineering professional.

Two faculty members of the EE department at ASU were interviewed. One of the faculty members was the chair of the graduate program in the EE department. The other faculty member was a junior faculty who actively conducts research in optical networking and is considering teaching a course in optical networking.

Five graduate students from the EE department at ASU were interviewed during a focus group session. Two of the graduate students have strong research interest in the optical networking area and conduct research in the optical networking field. The students ranged in their experience in optical networking from beginner (first year Ph.D.) to advanced (Ph.D. candidate). All the students were enrolled in the Ph.D. engineering program.

5. Quantitative Results

In this section, the most important quantitative results of the needs assessment are presented, specifically the results from the online survey distributed nationwide are presented. The results are organized by the main areas that this needs assessment addresses. Generally, the survey data obtained from the ASU respondents are consistent with those of the respondents from the broader engineering community. Minor differences are pointed out in the discussion. Note that the rating scale implemented in the online survey ranged in numerical values from 3 (strongly agree) to 0 (strongly disagree).

5.1 General need

Nationwide, 51 out of the total of 61 respondents (84%) agreed or strongly agreed with the addition of an optical networking course to the engineering graduate curriculum ($M = 2.47$). Specifically, 30 respondents strongly agreed, 21 agreed, and four disagreed. There was no strong disagreement.

Table 1. depicts the differences in perceptions of the importance of an optical networking course in the graduate engineering curriculum. The data suggest that engineering professionals have the strongest preference.
Table 1. Overall need for an optical networking graduate engineering course

<table>
<thead>
<tr>
<th>Current Status</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students</td>
<td>2.51</td>
</tr>
<tr>
<td>Faculty</td>
<td>2.31</td>
</tr>
<tr>
<td>Professionals</td>
<td>2.75</td>
</tr>
</tbody>
</table>

The extracted results of the online survey of ASU EE graduate students, faculty, and an engineering professional support the idea of offering a graduate level course in optical networking at ASU ($M = 2.35$). Specifically, approximately 90% of the all the respondents ($n = 32$) either agreed ($n = 14$) or strongly agreed ($n = 14$) that there is a need for an optical networking graduate course at ASU.

5.2 Course focus

As shown in Figure 1., the responses from the ASU survey and the nationwide survey (aggregates reported) indicate that a course focus on “Understanding of basic mechanism in optical networking” was ranked the highest (aggregate $M = 2.59$), followed by “Understanding of current trends in optical networking” as the second highest (aggregate $M = 2.45$). The lowest ranked course focus area was “Designing and evaluating protocols for optical networks” (aggregate $M = 2.21$). All the course focus areas had a mean score larger than 2.0 ($M$ ranging from 2.21 to 2.59), indicating an agreement with having these areas to be the course focus.

It is interesting to note that all the respondents (faculty, students, engineering professionals) ranked the focus areas approximately equally. However, the engineering professionals had slightly higher preference for more practically oriented focus areas compared to faculty. Specifically, the mean score for faculty for the focus area “Designing optical networking architectures” was 2.05 compared to the mean score of 2.83 for the engineering professionals. The same trend ($M = 2.15$ for faculty and $M = 2.83$ for the engineering professionals) was observed in the focus area “Designing and evaluating protocols for optical networks”.

![Optical Networking Course Focus](image)

Fig. 1. Optical networking course focus
5.3 Optimal content

The syllabi and course descriptions from the 14 universities across the US were analyzed. It was found that the main course content includes architectures and hardware, access, scheduling methods, protocols, control and management, protection, and WDM. The content topics and frequency are summarized in Table 2.

Next, we present the analysis of the survey responses on the course topics. The topics falling under the General Principles were ranked as the most important content to cover in an optical networking course (mean score ranged from 2.40 to 2.81, aggregate overall $M = 2.55$). The ranking of the subtopics within the General Principles topic was in the order from highest to lowest importance given by: WDM/ DWDM; layered/hierarchical network architecture; 1st to 3rd generation of optical systems. This ranking appears to indicate the principles that are valid for all optical networks (WDM/DWDM and layered/hierarchical network architecture) are considered more important than the historical overview of the development from 1st to 3rd generation optical systems.

The other content areas and topics within optical networking were also ranked as important, specifically, the aggregate mean scores for the topics within the Architectures and Hardware area ranged from 2.28 to 2.49 (overall $M = 2.39$), for the Protocols topics the aggregate mean ranged from 2.16 to 2.68 (overall $M = 2.44$).

The respondents of the survey mailed on the ASU EE mailing list rated the three main content areas (Architectures and Hardware, Protocols, and General Principles) roughly as equally important. The overall combined mean scores for these three content areas on the survey was 2.41 (Architectures and Hardware 2.42, Protocols 2.39, and General Principles 2.53). This indicates a rating that falls between the agree (2) and strongly agree (3) category.

5.4 Delivery method

In terms of the optimal delivery method, the survey respondents ranked an Entirely Face-to-Face (traditional) method of course delivery as the most optimal ($M = 2.38$). The respondents also highly ranked the hybrid (Emphasize Face-to-Face Classroom Activities with Online Readings and Assignments) form of course delivery ($M = 2.33$). The aggregate online survey results show a large gap between the mean scores of the most favorite delivery method (Exclusively Face-to-Face, $M = 2.38$) and least favorite delivery method (Entirely-Online, $M = 0.58$). 88% of the respondents explicitly disagreed (27%) or strongly disagreed (61%) with delivering the course entirely online.

The data obtained solely from the ASU respondents are consistent with the general results of the nationwide online survey. The ASU survey showed a large margin between the most and the least favorite delivery method. 90% of the ASU respondents preferred the course to be delivered exclusively face-to-face, and 80% of the ASU respondents explicitly disagreed (27%) or strongly disagreed (53%) with the entirely online course delivery method. The mean score rating for the Exclusively Face-to-Face course delivery method was 2.50, which sharply contrasts with the mean rating of 0.77 for the Entirely Online course delivery method.

It is interesting to note that the hybrid course delivery method, which emphasizes face-to-face classroom activities but combines those with online readings and assignments, received a relatively high ranking (national aggregate $M = 2.33$, ASU $M = 2.17$). This delivery method is aligned with the ASU distance education goals (to become a leader in distance education). The assumption is that this hybrid course delivery method would improve accessibility, resource utilization, and revenue. Second, from the limited overall sample of the engineering professionals ($n = 6$), it appears that the engineering professionals have higher preference for entirely online instruction ($M = 1.00$) than the graduate engineering students ($M = 0.47$). The differences among the three groups (faculty, students, and engineering professionals) can be observed in Figure 2.
Course Delivery Method

5.5 Teaching materials

The preferences for teaching materials expressed in the online surveys are illustrated in Figure 3. The textbook received the highest rating from the online survey participants ($M = 2.63$). There is a slight difference between ASU and the rest of the national sample in the second preferred teaching material. The ASU respondents preferred the “Collection of Examples (real models, animated applets)” ($M = 2.57$) whereas in the nationwide survey, “Instructor Slides (contents)” were ranked as the second highest ($M = 2.53$). The Database of Test Questions was generally ranked the lowest ($M = 1.86$).
5.6 Prerequisite knowledge

In terms of the prerequisite knowledge that students need to acquire before taking a graduate course in optical networking, the online survey respondents rated Networking Basics (TCP/IP) as the most important \( (M = 2.41) \). The second highest ranked prerequisite knowledge was Fiber Optics Basics (Lasers, Detectors, Fibers) with \( M = 1.95 \). This was followed by Performance Evaluation Basics (Stochastics, Simulation) prerequisite knowledge \( (M = 1.90) \). The second to last in prerequisite knowledge importance was ranked Wave Physics \( (M = 1.38) \). The lowest rating of prerequisite knowledge was Advanced Networking (MPLS, Differentiated Services) with \( M = 1.31 \).

An interesting finding emerged during the analysis of the group (faculty, students, engineering professionals) differences. Faculty rated the fiber optics basics (lasers, detectors, fibers) topic as not very important prerequisite knowledge \( (M = 1.55) \). This result contrasts with ratings of the same prerequisite knowledge area by the engineering professionals \( (M = 2.50) \).

6. Qualitative Results

The presentation of the qualitative data includes the analysis of the extant data, the analysis of the qualitative responses and the comments obtained from the online survey, the comments collected during interviews with the subject matter experts, and the observations from the focus group with graduate engineering students.

6.1 Extant data

The analysis of the extant data (optical networking course syllabi and course descriptions from 14 universities across the US) revealed that the main content in a graduate level course in optical networking covers a broad spectrum, including architectures and hardware, access, scheduling methods, protocols, control and management, protection, and wavelength division multiplexing (WDM). The majority of the courses included homeworks, lab sessions/demonstrations, and projects (applied or theoretical). The homeworks were intended to reinforce the concepts learned in classes. All the courses had exams as an assessment method of student performance. The most commonly used textbooks were *Optical Networks: A Practical Perspective* [4], *Fiber Optic Communication Systems* [5], and *Optical Communication Networks* [6].

6.2 Qualitative data analysis

The qualitative data from the write-in comment fields in the online survey suggest that the respondents strongly support the idea of offering a graduate level course in optical networking for engineering students. Respondents generally consider optical networking as an emerging technology that meets the demand of high-speed communication and cost reduction. Optical networking is perceived as the future of networking, replacing copper wire networks. One respondent sees the optical communication industry as the “latest job-providing field well worthy of exploration.” The understanding of optical networking is viewed essential to engineers in the industry. Accordingly, a graduate level course in optical networking would help prepare the students for the future; therefore good engineering programs should offer such a course.

In terms of the instructional content, the respondents would like the students to be aware of the state-of-the-art technology on the market. Because optical networking has a broad range of topics, it is important that the instructors clearly state the course focus. A few respondents would prefer to include an undergraduate preparatory course or to cover topics such as routing, flow control, and networking in a general scope engineering course.

Flexibility should be given to students if they are interested in a particular topic, including making this course an elective instead of a core course. It was suggested that conference and journal papers should be included as teaching materials.

6.3 Interview

The interviews with two ASU EE professors indicate that optical networking is an emerging area of research interest. It appears that the EE department at ASU is generally optimistic about the idea of offering a graduate course in optical networking. Numerous faculty members conduct research in optical networking and related fields. The interviewees felt that the topic of optical networking fits well into the graduate engineering curriculum at ASU and might be a worthwhile addition to the engineering program. The interviewees perceived the EE department as
having sufficient resources (facilities, personnel, equipment, instructional support, etc.) that would be available for a graduate course in optical networking.

The interviewees agreed that students should have some basic understanding of general networking principles and light physics before taking a graduate course in optical networking. There was a consensus between the interviewees in regard to the course focus. The course should focus on the design, analysis, and implementation of optical networks. Furthermore, the course should cover optical networks architectures and hardware, protocols, and specialized topics.

There were some concerns expressed by the interviewees in regard to the potential enrollment in the course. Specifically the number of students who would be interested in the course might be low due to the currently limited employment opportunities in the optical networking field, which is currently in a recession. However, both interviewees are positive about the future of the optical communications and networking industry and foresee the market as improving, thus leading to increased interest in optical networking education among graduate students as well as job opportunities in the optical networking area.

6.4 Focus group

The focus group with five ASU EE graduate students indicates that optical networking is still an emerging research area. Generally, the students did not know extensively about optical networking. They had some basic knowledge that they gained in undergraduate engineering classes. Two of the respondents had a high degree of specialized knowledge in optical networking, since they selected the field as an area of active research and study. The students expressed interest in introductory as well as advanced / specialized contents in optical networking. However, those students who did not select optical networking as a research area would be only partially interested in taking a formal graduate course in optical networking. This is due to the course content not being compatible with personal research interests, and the currently limited market demand for professionals in the optical communications and networking field. All students reported their preference for the lecture delivery format, which they perceived as an efficient way of content delivery. The students also valued projects and problem-solving scenarios, since they might be a better measure of performance. In addition, the students perceived that they learn more by actually producing something than by recalling information on a quiz. The students preferred the face-to-face course delivery method. In their opinion, this instruction allows for enhanced interaction among the learners, and promotes the student-professor interaction. This is consistent with the findings from the online survey. In addition, the students were able to recognize some of the advantages of distance education, especially flexibility. However, they were concerned about the available technical support for a distance education course, and interactivity. (This concern may in part stem from the quite extensive technical difficulties and outages that student IT system at ASU had experienced in the fall 2002 and spring 2003 semesters.) The students felt strongly about the option to have face-to-face meetings with the instructor even if the course was offered in the distance education (online) format.

7. Implications and Recommendations

Overall, the collected data indicate that there is a need for the ASU EE department to offer a graduate course in optical networking. Specifically, the data from the ASU respondents suggest that 90% of the respondents either agreed or strongly agreed that there is a need for an optical networking graduate course at ASU. None of the respondents reported strong disagreement. Such need is echoed nationwide. Overall, the majority (84%) of the sample of the engineering community perceived optical networking as a necessary part of graduate engineering curriculum. The ASU EE department has sufficient resources, including facilities, personnel, and instructional support to support the implementation of a graduate course in optical networking.

The collected qualitative data indicate that optical networking should be included in graduate engineering programs. The attitudes toward optical networking in general were very positive among all of the respondents. The sample from the engineering community (students, faculty, and engineering professionals) reported that optical networking should be taught in graduate engineering schools to better prepare students for the future. The engineering community perceives optical networking as an emerging area of research that is likely to grow; given the communication industry comes out of the currently experienced recession.

In terms of the contents of a graduate level course in optical networking, it is recommended that the following should be covered: (i) General Principles (in the descending order of importance: WDM/DWDM; layered/hierarchical network architecture; 1st to 3rd generation of optical systems), (ii) Protocols (in the descending order of importance: routing and wavelength assignment; protection and restoration; switching; TCP/IP over WDM; medium access; grooming; MPLS), and (iii) Architectures and Hardware (in the descending order of importance:
switches/amplifiers/routers; mesh; ring; single-hop; access/metro network; backbone). The results support the idea of broad instructional content being taught in a graduate level course in optical networking.

Since a textbook is used / considered as the primary tool for supporting teaching, it is suggested that a graduate optical networking course is based on a textbook. The data also indicate that the course instructors could include slides (to present content) to support teaching. Therefore, it might be advisable to design and develop presentation slides to impart knowledge and to reinforce the most important content. Those presentation slides would be aligned with the textbook and the overall course objectives to facilitate learning.

Based on the analyzed data, it is recommended that a graduate course in optical networking is delivered either by traditional means (exclusively face-to-face instruction) or in a hybrid form, which emphasizes face-to-face classroom activities but combines those with online readings and assignments. However, considering the high rate of disagreement, it is not recommended to use an entirely online format of a course delivery.

8. References


9. Appendix

Online survey form
The purpose of this survey is to collect data on the role of Optical networking in graduate instruction. Please fill out the survey by checking the options that best represent your opinions for each statement. Your input is very valuable.

<table>
<thead>
<tr>
<th>SA - Strongly Agree</th>
<th>A – Agree</th>
<th>D – Disagree</th>
<th>SD - Strongly Disagree</th>
</tr>
</thead>
</table>

1. The prerequisite knowledge a student should have before taking a course in Optical networking is:
   - Networking Basics (TCP/IP)  
   - Fiber Optics Basics (Lasers, Detectors, Fibers)  
   - Performance Evaluation Basics (Stochastics, Simulation)  
   - Wave Physics  
   - Advanced Networking (MPLS, DiffServ)  

2. The focus of a course in Optical networking should be on knowledge/skills in:
   - Understanding of Basic Mechanisms in Optical networking  
   - Understanding of Current Trends in Optical networking  
   - Understanding Interrelationships between Technology, Architecture, and Applications  
   - Designing Optical networking Architectures  
   - Designing and Evaluating Protocols for Optical Networks  

3. Which of the following ARCHITECTURES & HARDWARE topics should students learn?
   - Single-Hop (Star)  
   - Ring  
   - Mesh  
   - Switches / Amplifiers / Routers  
   - Backbone  
   - Access / Metro Network  

4. Which of the following PROTOCOLS topics should students learn?
   - Routing and Wavelength Assignment  
   - Protection and Restoration  
   - Medium Access  
   - Switching (Packet, Burst)  
   - Grooming  
   - TCP/IP over WDM  
   - MPLS  

5. Which of the following GENERAL PRINCIPLES topics should students learn?
   - WDM, DWDM  
   - Layered / Hierarchical Network Architecture  
   - 1st to 3rd Generation of Optical Systems  

6. What kind of materials / strategies would you use to support your teaching?
   - Textbook  
   - Instructor Slides (Content)  
   - Collection of Examples (Real Models, Animated Applets)  
   - Workbook of Homework Problems  
   - Solution Guide to Homework Problems  
   - Database of Test Questions  
   - List of Discussion Topics  

7. What would be the optimal delivery method for a graduate course in Optical networking?
   - Exclusively Face-to-Face Classroom Activities  
   - Emphasize Face-to-Face Classroom Activities with Online Readings and Assignments  
   - Half Online Activities and Half Classroom Activities  
   - Emphasize Online Activities with Classroom Meetings  
   - Entirely Online (Class Never Meets Face-to-Face)  

8. Overall, it is necessary to offer a graduate course in Optical networking to engineering students.  

SA A D SD
20 years of graduate optics education at the University of New Mexico

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Abstract: The year 2003 marks the 20th anniversary of introducing interdisciplinary graduate optics education at the University of New Mexico. The Ph.D. program in Optical Sciences has produced over 75 graduates. A new M.S. program in Optical Science and Engineering, introduced in Fall 2002, is rapidly gaining popularity. This paper reviews both programs, focusing on their unique features.

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1. Introduction

For the past 20 years, the Departments of Physics and Astronomy (P&A) and of Electrical and Computer Engineering (EECE) at the University of New Mexico (UNM) have jointly administered a highly successful interdisciplinary, intercollegiate Ph.D. program in Optical Sciences. During this interval, over 75 Ph.D. degrees have been awarded to graduates who have become highly valuable members of optical industries and academia here and abroad. During this same period, the optics-related faculty has seen its numerical strength increase to nearly 30, and has expanded into several departments such as Biology, Chemistry, Mathematics and Statistics, Chemical Engineering, and Mechanical Engineering.

The graduate program in optics at UNM is evolving continually to adapt to the growing needs of the entire optics enterprise of industries, federal laboratories, and academic institutions. Over the last few years, attention has turned to the establishment of a Master’s degree in Optical Science and Engineering (OSE) at UNM. A distinctive feature of the new multi-disciplinary degree is its unique Internship option, which allows a student to spend six months to a year at a participating industry or a federal/national laboratory working on a scientific project of mutual interest. Additionally, the Internship would accord the industries and labs a first-hand look at prospective employees and ability to “pre-train” them, creating in the process further collaborative activities between UNM and optics industry/labs. In these ways, the new degree is expected to fulfill a long-standing need for industrial and lab personnel that are well trained in relevant and meaningful ways to meet the challenges of the 21st century. The desirability of a Master’s degree is substantial in other respects too, particularly for short-term retraining of already employed optics personnel, for giving the university a stronger role in creating business opportunities and economic benefits that would result from a broader interaction with industrial and government laboratories, and for creating an optics career path with multiple exit points. The new degree has received strong support from the New Mexico Optics Industry Association (NMOIA), which represents a large number of optics industries in the State of NM, and from a variety of other organizations which see substantial overall benefits to the State from such a program.

Currently, 9 students are enrolled in the M.S. in OSE program through the P&A Department, and 7 through the EECE Department. Corresponding enrollment numbers for students in the Ph.D. in OSE program are 29 through P&A, and 16 through EECE. These numbers are expected to grow steadily in the future years, especially when the new B.S. in OSE degree program, presently in its advanced planning stages, is introduced.

2. The setting

The rustic setting of New Mexico populated along the meandering waters of the Rio Grande belies the hubbub of intense industrial and scientific activity in its three major research universities, three federal laboratories, and numerous industrial establishments. The state that is sometimes confused for the country it borders to its south boasts a long tradition of pioneering research in science and technology, ranging from the heady times of rocketry
and the harnessing of nuclear energy through the cold-war era of quiet but highly prominent research in optical imaging and reconnaissance at the Air Force Research Laboratory. The present times definitely belong to optics and photonics, a discipline that has long played – and continues to play – the role of enabling a vast number of important technologies ranging from manufacturing to biomedical engineering to modern high-bandwidth communication to highly efficient, bright display devices.

Nestled between the foothills of the majestic Sandia Mountains and the idyllic Rio Grande river, Albuquerque, the largest city in New Mexico boasts frequent spectacular double rainbows as well as an array of national and federal laboratories, numerous optics and photonics industries, and a Carnegie Doctoral/Research university with a major degree program in optics. Research and education in optical science and engineering have a long, distinguished history in New Mexico, and the two aspects of optics have strengthened each other, in particular over the past two decades. And the university that has led a lot of this activity was accorded the status of the fastest growing research institution in the country just four years ago, when measured in terms of the overall federal research dollars attracted.

UNM joined the ranks of the Universities of Rochester and Arizona in 1983 with its Ph.D. program in Optical Sciences, established by the joint will of its Physics and Astronomy (P&A) and Electrical Engineering and Computer Engineering (EECE) departments. Currently one of only five major graduate degree programs in optics in the US, UNM’s program sets itself apart, already at inception, from its two more illustrious original peers, Arizona and Rochester, by choosing a cross-disciplinary focus as its principal motivation. In this respect, it anticipated by fifteen years the findings of the now widely cited, comprehensive COSE report of the National Research Council, 1998, which proclaimed:

“Universities should encourage multidisciplinarity in optics education, cutting across departmental boundaries, and should provide research opportunities at all levels, from the bachelor’s degree to the doctorate and from basic science to applied technology.”

The Ph.D. program at UNM has produced over 75 optics Ph.D.’s, all well employed in a variety of national and international settings. The two participating departments have shared in the design and teaching of the core and ancillary courses and performed pace-setting research in many areas, notably ultrafast optics and photonics, high-resolution imaging, quantum optics, optoelectronic devices, fiber amplifiers, optical materials, and novel optical lithography. The breadth and depth thus attained by the program have unquestionably created a world-class training, education, and research facility at UNM.

Led by twenty optics faculty members spread equally over the two participating departments, the graduate program in optics is supported by 5,000 sq. ft. of research laboratory space within P&A and a new 60,000-sq.ft. Center for High Technology Materials (CHTM) building with 18,000-sq.ft. of dedicated space for optoelectronics and laser research. The facilities and instruments at the disposal of our students in these buildings include a 4,000-sq.ft. class-100 clean room and several class-10,000 clean rooms, microlithography and thin-film deposition facilities, two MOCVD and one MBE crystal-growing facility; several short-pulse laser systems, including high-power femtosecond UV and Ti:sapphire as well as fiber lasers and amplifiers, dye and solid-state lasers; and a variety of other instruments that include materials diagnostic apparatuses like scatterometer, ellipsometer, x-ray diffraction probes, etc. and photolithographic, vacuum processing, and related systems.

Each year, only a small fraction of the applicants to the Ph.D. program are admitted. Almost without exception, those accepted are supported by a number of teaching and research assistantships dedicated to this degree program.

A key beneficiary of a strong optics education and research program at UNM has been optical astronomy and imaging. Imaging has great relevance to the Air Force, which has strong research in these areas at its Research Laboratory (AFRL) at the Kirtland Air Force Base (KAFB) and has supported important imaging projects at UNM. The precious dark skies of NM have rendered excellent astronomical opportunities and led to world-class observational facilities like the Very Large Array near Socorro just eighty miles away, the National Solar Observatory near Cloudcroft about two hundred miles away, a large telescope outfitted with state-of-the-art adaptive optics system at the Starfire Optical Range (SOR) at KAFB, among others. The role of optics at UNM is also considerable for UNM’s Lodestar project, a federally and state-funded thirty-million –dollar program to create a state-wide educational and research infrastructure in astronomy from the grade levels to the most advanced doctoral research levels.

Very noteworthy developments in high-power lasers, including the chemical oxygen-iodine laser (COIL), the CO2 laser, and the CO laser, at AFRL have led to further collaborative projects at UNM. Similarly important collaborations, including laser-induced cooling, have marked our relationship with the Los Alamos National Laboratory (LANL), only ninety miles away, and with the Sandia National Laboratory (SNL) located within the city limits.
The unique local setting of the three important government laboratories, AFRL, LANL, and SNL, and their cooperative venture with UNM’s Center for High Technology Materials (CHTM) under the Alliance for Photonic Technology (APT) have led to a strong emerging collaboration with US industries. The connection with numerous local optics industries has been further bolstered by the active presence of the recently formed NMOIA. The combination of APT and NMOIA provides for a formidable collaborative infrastructure for optics education and research in New Mexico.

3. Early history

Through the 1960’s and 70’s there emerged two universities in the United States where optics was an important component of the curriculum and research program. Through the 70’s both of these institutions have grown and prospered. These are the University of Rochester, long noted for its interest, emphasis, and research on optics, and the Optical Sciences Center at the University of Arizona, formed in response to the perceived need for increased activity in optics in early 1970’s. By 1980, these two institutions trained the bulk of graduates in the optical sciences at the M.S. and Ph.D. degree levels. Of the roughly 70-80 Ph.D.’s in optics graduated each year in the United States, about 20 came from the University of Rochester, 20 from the Optical Sciences Center at the University of Arizona, and the rest from the 20 or so departments around the country, with each of which producing 1-2 graduates a year.

Through the decade of 1970’s, optics-oriented industries have been formed and have expanded at a rapid rate. By 1978, over $5 billion per year was being spent by industry and Government on optics and optical systems. There were more than 1,000 optical scientists, and in the Albuquerque area alone there were about a dozen companies involved in optics research. Most of these provided services via contract to programs at Kirtland Air Force Laboratory, Sandia National Laboratories, or Los Alamos National Laboratory.

By the end of 1970’s, officials of these companies and laboratories were urging UNM to establish an optics program. The advantage was clear and three-fold. First, it would provide the much-needed manpower base to these companies and federal laboratories; second, it would provide an opportunity for New Mexicans to gain education in this rapidly developing field and find excellent employment opportunities locally; third, it could provide for retraining or upgrading the skills of personnel working on optical projects for local laboratories. For example, the Kirtland Air Force Laboratory was sending their scientists for a year to the Optical Sciences Center at the University of Arizona to be retrained in the optical sciences area. The cost and logistical disadvantages associated with this approach were clear. It would be of great assistance to the programs at Kirtland if training opportunities in the optical sciences were available locally.

In 1980/81 the P&A Department established a research and instructional group called the Institute for Modern Optics (IMO). The original personnel consisted of Marlan Scully and his research group who joined UNM from the Optical Sciences Center at the University of Arizona in 1980. In the first year the following courses were established and offered through the P&A Department: 476L/447L – Experimental techniques of Optics, 554 – Advanced Optics I, 555 – Advanced Optics II, 556 – Electro-Optical Physics, 564 – Laser Physics I, 565 – Laser Physics II, 566 – Nonlinear Optics and High Power Lasers. These new courses along with previously established graduate courses in physics allowed the department to offer the basics of advanced optics and laser physics.

The response to this expanded academic program was very positive. Enrollment in graduate-level courses was rising. A substantial fraction of the enrollment was from scientists and engineers who were not otherwise pursuing a university degree. Through their experience with the courses offered in 1980/81 and through numerous discussions with scientists and administrators in local industry and federal laboratories, the IMO group reached the conclusion that there was strong local interest in a broader range of courses in the area of optics, laser optics, and optical systems engineering, and that there was a significant demand for a degree program in optical sciences and engineering.

Recognizing the truly interdisciplinary nature of optics, with elements of physics, applied physics, materials science, and engineering, the IMO group proposed establishment of a new interdisciplinary degree program at UNM, with initial participation from the P&A and EECE departments, as well as from IMO.

In the late 1970s and early 1980s, the EECE Department developed its interest in the area of microelectronics. In 1981, a departmental report formulated "plans to focus on the areas of microelectronics and computer engineering. These are two areas in which they expect the most significant growth over the next ten years."

Two years later, in 1983, the EECE Department established an Endowed Chair in Microelectronics with the financial backing of the city of Albuquerque and the state of New Mexico and, at the same time, established the Institute for Microelectronics and Thin Films (IMTF). During this period, the EECE Department and the Physics Department under the guidance of Dr. Scully established a joint Ph.D. program in Optical Science and Engineering. These
developments came about due to the continued growth of the field of microelectronics and optoelectronics, the
newest research and teaching interest in the Department.

The first recipient of the endowed chair in microelectronics was William Streifer, who in 1985 joined UNM and
became the Director of the CHTM. Following the arrival of the new director, the CHTM was reorganized to include
the IMO and the IMTF. Each institute became an interdepartmental entity reporting directly to the center director.
To assist the director, coordinators have been appointed for each institute; specifically, Charles Hart in the IMO and
Kenneth Jungling in the IMTF.

The first home of the CHTM under William Streifer’s tenure was the Tapy Hall, the building named after Ralph
W. Tapy who headed the Electrical Engineering Department from 1939 till 1952. The building also housed part of
the overcrowded EECE department that occupied also part of the Farris Engineering Center, the Mechanical
Engineering Building and the Old Lecture Hall.

Under William Streifer’s leadership, strong focus on research in optoelectronics was established at CHTM, and
this area has remained the main activity at CHTM till present. In 1986, Steven Brueck became the new director of
the CHTM. He continues to lead the Center till today.

In 1982 a state-issued building bond came to maturity. Under the leadership of Chairman Peter Dorato,
construction of the new EECE building started. The much-needed structure was completed in the summer of 1986
and continues to house the EECE Department to this day. CHTM has moved to the basement of this new
EECE/Centennial Library building and stayed there until 1997, when it was transferred to a newly dedicated
building located in the Science and Technology Park on south campus of UNM.

Already in 1980/81, 7 optics-related graduate-level courses were offered at the P&A Department, and 3 more
were offered by 1982/83, focusing heavily on laser physics. In parallel, 7 optics-related graduate-level courses
were proposed by 1982 at the EECE Department, with emphasis on optical design and testing. While some of these early
offerings still remain in the core of the Ph.D. program, many new courses have since been developed, particularly in
the areas of semiconductor optoelectronics and photonics.

4. Optics faculty at UNM

Currently, nearly 30 faculty members participate in OSE graduate programs. While most of them are affiliated with
either P&A or EECE departments, several faculty associated with the program reside in other departments in the
College of Arts and Sciences and in the School of Engineering. The following list identifies the participating faculty
and briefly summarizes their research interests.

Alejandro Aceves, Mathematics & Statistics: Nonlinear optics, nonlinear dynamics
James A. Brozik, Chemistry: Spectroscopy
Steven R. J. Brueck, EECE: Imaging interferometric lithography, extending optics to fundamental limits
Carlton Caves, P&A: Quantum information theory and quantum measurement theory, particularly on ways of using
quantum mechanics to perform information-processing tasks that cannot be performed classically
Christos Christodoulou, EECE: Helical THz antennas on semiconductor substrates, finite-difference analysis of
phased array antennas, smart antennas in wireless communications, neural networks and modeling of
electromagnetic systems
L. Ralph Dawson, EECE: MBE growth of narrow gap III-V semiconductors, like group-III antimonides, for
detectors and emitters
Ivan H. Deutsch, P&A: Quantum information theory with emphasis on atomic-molecular-optical implementations
based on laser cooled and trapped atoms
Jean-Claude Diels, P&A: Experimental investigation of ultrafast phenomena, development of femtosecond laser
sources, optical imaging using femtosecond range gating, nonlinear optics
Petr G. Eliseev, EECE: Semiconductor lasers, quantum dots
Arthur H. Guenther, EECE: Laser applications to pulsed power technology, laser induced damage to optical
materials, optics in defense, optics education
Majid Hayat, EECE: Optical communication, modeling and optimization of avalanche photodiodes, design and
performance analysis of ultrafast optical links, statistical communication theory, signal detection and
estimation, statistical image and signal processing, nonuniformity correction algorithms for infrared focal-
plane array sensors, imaging through turbulence, communication networks, congestion modeling and control
Stephen D. Hersee, (Ph.D., Brighton Polytechnic, 1975), EECE: MOCVD growth of III-V semiconductors
Diana Huffaker, EECE: Crystal growth (MBE, MOCVD) and characterization of novel materials for optoelectronic
devices, growth methods and characterization of quantum dots for single photon, single electron based
devices, photonic lattice fabrication and characterization, optical interconnects and integrated optoelectronics based on VCSEL technology

Ravi Jain, EECE: Quantum electronics, optoelectronics, electro-optics, experimental solid-state physics
V. M. Kenkre, P&A: Theory of light-matter interactions in organic materials, exciton formation and dynamics, laser damage and ultrafast processes
Sanjay Krishna, EECE: Mid-infrared detection using self-organized quantum dots (QDs) and novel antimonide-based materials grown by molecular beam epitaxy
Luke Lester, EECE: Quantum dot lasers, mid-IR semiconductor lasers, and tunable lasers
Gabriel J. Lopez, Chem. & Nuclear Eng.: Self-assembled nanostructures
Kevin Malloy, EECE: Coherent states in semiconductors, disorder in ionic semiconductors, wave propagation in periodic structures
Jack McIver, P&A: High-power lasers
Marek Osinski, EECE: Semiconductor lasers, optoelectronic devices and materials, group-III nitrides, degradation mechanisms and reliability, computer simulation, optoelectronic integrated circuits
Sudhakar Prasad, P&A: Classical and quantum optics, particularly the application of optical fibers in imaging interferometers, studies of sensitivity and resolution of such interferometers, statistical information in interferometric image processing, and studies of quantum noise in resonant atom-field interaction
Wolfgang Rudolph, P&A: Ultrashort laser pulses and spectroscopy, femtosecond microscopy, infrared lasers
Edl Schamiloglu, EECE: Plasma physics, charged particle beams, electromagnetic wave propagation
Thomas Shay, EECE: Free-space optical communications through clouds, quantum cryptography, lasers
Mansoor Sheik-Bahae, P&A: Laser cooling of solids, ultrafast phenomena, nonlinear optics
Stephen A. Stricker, Biology: Optics in microbiology
Scott Tyo, EECE: Ultra wideband antennas and radiation, optical and microwave remote sensing, hyperspectral and polarimetric imagery, metamaterials and artificial dielectrics
James Thomas, P&A: Biological applications of ultrafast spectroscopy
Krzysztof Wodkiewicz, P&A: Quantum optics

5. Ph.D. in Optical Science and Engineering

The requirements for the Ph.D. degree in OSE include:

- 52 hours of course work for credit, including 30 hours in required courses. To account for the diversity of interests in Optics, the 30 credit hours of required courses have been divided into two categories (see A and B below);
- 18 dissertation credit hours;
- Comprehensive Exam;
- Dissertation and defense

A. Mandatory courses (27 credit hours):
   Advanced Optics I (Physics 463 or EECE 463)
   Advanced Optics II (Physics 554 or EECE 567)
   Laser Physics I (Physics 464 or EECE 464)
   Mathematical Methods in Physics (Physics 466 or Math 466)
   Electromagnetism (Physics 511 or EECE 561)
   Quantum Mechanics I (Physics 521) or Semiconductor Properties (EECE 572)
   Nonlinear Optics (Physics 555 or EECE 568)
   Optics Lab (Physics 476L or 477L)

   3 credit hours of seminar, including one Optics seminar

B. Option-based courses (3 credit hours):
   Solid State (Physics 530) or Semiconductor Properties (EECE 572)
   Topics in Modern Optics (Physics 569)
   Guided Wave Optics (EECE 564)
   Mathematical Methods of Physics (Physics 467)
   Laser Physics II (Physics 564) or Semiconductor Laser I (EECE 577)
   Quantum Mechanics II (Physics 522)
The remaining 22 credit hours of coursework can be satisfied with a combination of “B” courses (500 level or above), including problem courses and research hours.

5.1. The Optics Comprehensive Exam

The Optics Comprehensive Exam is offered at the beginning of each Fall term concurrently with the Physics and EECE Comp Exams, and is based on material derived from Physics 463 or EECE 463, Physics 554 or EECE 567, Physics 464 or EECE 464, and Physics 511 or EECE 561. The exam itself consists of three parts - within 12 months of successfully completing the written and oral exams, a presentation by the student must be accepted by a committee. The intent of this presentation is to show that the student (i) has found a dissertation advisor, (ii) has formed a dissertation committee, and (iii) has started with research. Possible presentations are, for example, the defense of a research project or a dissertation proposal. Students do not advance to candidacy and, therefore, are not eligible to register for dissertation hours (699), until the presentation has been approved by the committee.

5.2. The Oral Exam

All students who take the written section of the Optics Comprehensive Exam are administered an oral exam by their Committee on Studies. Exception to this ruling is only rarely permitted, and is decided by the Committee on Studies prior to scheduling the oral exam. The Optics Graduate Committee is the body empowered to make the final decision on the Committees’ pass/fail recommendations.

5.3. The Dissertation Proposal

After passing the comprehensive exam, the student is expected to either obtain a dissertation research problem from a faculty member, or to formulate an independent dissertation proposal. The student should present this dissertation proposal to his or her Dissertation Committee as soon as possible, but no later than one year after the date of passing the Comprehensive Exam. At least two members of the Dissertation Committee, including the Chair, should be Optics faculty. If the dissertation proposal is deemed adequate as a starting point for a Ph.D. dissertation, then the student can formally advance to candidacy and begin dissertation work.

6. M.S. in Optical Science and Engineering

Over the years, a strong need for Master’s program in Optical Science and Engineering (OSE) has been felt by students and faculty alike. A survey among the optics students in the Ph.D. program carried out few years ago showed an overwhelming support for an M.S. degree. Contact with national laboratories in Albuquerque are, namely Sandia National Labs., Air Force Research Lab. (Kirtland AFB), and Los Alamos Research Lab., has also revealed great interest in such a program. Market surveys done both by the National Research Council (NRC) and SPIE were also indicating a growing need for short-haul specialized training, as provided ideally by the Master’s degree rather than the Ph.D. In particular, a study by the NRC, completed in 1998, on the state of optics and photonics was unequivocal in its prediction that the need for well trained optics personnel at all levels in industrial settings will easily outstrip their supply from the relatively few institutions that offer specialized optics degrees.

With the overwhelming evidence to indicate the desirability of the Master’s program, further strengthened by enthusiastic endorsements from New Mexico Optics Industry Association, Albuquerque Economic Development, Inc., NM Department of Economic Development, and the Albuquerque Chapter of the Optical Society of America, a plan for a new M.S. in OSE degree was formulated in January 1999. Similarly to the Ph.D. program, the Master’s program was prepared as an interdisciplinary offering, administered jointly by the P&A and EECE departments. The process of formal approval of the program at various university and state levels was completed in May 2002, when the State Board of Finance acting upon recommendation from the Commission for Higher Education voted to approve the program. The first students were recruited into the Master’s program in Fall 2002. Some students transferred from the pre-existing Ph.D. in Optical Sciences into the Master’s program, which resulted in the first M.S. alumna graduating already in the first semester it was offered.

In order to emphasize the equal role played by both P&A and EECE departments and to re-align the M.S. and Ph.D. curricula so that they would be well articulated, the name of the Ph.D. program has been changed to Ph.D. in OSE.

Recognizing that many M.S. students will be interested in working in industry or in the national laboratories upon their graduation, the program has an attractive option of industrial/government laboratory internship lasting
between six and twelve months. Short quarterly reports, as well as a comprehensive final report, must be submitted by the students to a committee consisting of a faculty liaison, another member of the optics faculty, and the student’s industrial or lab supervisor. An Industrial/National Lab Advisory Committee, consisting of R&D representatives from actively participating industry and labs, has been formed and is serving to further develop, refine, and oversee the internship option.

The M.S. degree in Optical Science and Engineering was approved enthusiastically in May 2002 both by the NM Commission for Higher Education and the NM State Board of Finance. Throughout its approval process through various university and state level committees and agencies, the program has received strong, often unreserved, endorsement as one fulfilling the vision of broad-based optics education, as well as enhancing and completing the highly successful graduate optics program which has already produced over 75 Ph.D’s. The MS program is an industrially driven initiative that is likely to help the NM optics industry meet its workforce needs from a local pool of uniquely qualified graduates. A similar industrial pulling led to the establishment of a new Associate of Applied Science (A.A.S.) degree program in photonics at the Albuquerque Technical Vocational Institute (TVI) in 2001. That program has already shown great promise in attracting large numbers of students, and is well deserving of its billing as an excellent model for production of highly skilled technicians for an industry that is likely to define and steer the economic development of the state and the nation in the new century. The new M.S. degree program at UNM has similarly drawn enthusiastic support from the entire spectrum of governmental and industrial establishments.

Like the Ph.D. program, the M.S. degree is being administered jointly by the departments of P&A and EECE. The joint involvement of a science and an engineering department in UNM’s graduate optics program underscores the cross-disciplinarity of this field.

The M.S. in OSE program has three different tracks to the degree, all of which share a required set of six courses divided equally between the basic science and engineering emphases of the field, but permit a student to either (i) complete further course work only or (ii) undertake research thesis work or (iii) sign up for an internship course along with other courses to complete the requirements of the degree. It is under option (iii) that a student will be able to perform a 6-month (to a year-long) internship either at an industry or at a federal government laboratory. This unique option, not available at any of the other four major optics programs in the country, will provide new opportunities for industry to supervise and evaluate potential future employees, to send its existing employees for further training, and for graduating students to preview and evaluate industrial career options. An Industrial/Laboratory Advisory Committee, consisting of representatives of NM’s commercial and government R&D sectors, will work closely with the Optics Graduate Committee at UNM to provide oversight needed to run this internship degree option effectively and adaptively with regard to evolving industrial needs and priorities.

Overall, the MS degree in Optical Science and Engineering at UNM will fill a unique role in the exploding optics enterprise of the state. By creating a local pool of highly skilled work force in this most important industrial sector, it will contribute significantly to defining the industrial economy of the state and the country for years to come.

6.1. M.S. curriculum

Plan I (thesis-based), a minimum of 24 hours of coursework and 6 hours of thesis credit (Physics 599) is required. Students must consult with a faculty member (Thesis Chair) about a research topic, and make a thesis proposal to the student’s Thesis Committee very shortly thereafter. The student must write an approved manuscript and successfully defend the thesis in a manner analogous to a Ph.D. dissertation defense.

Plan II-a (course-based) requires a minimum of 33 hours of coursework, including 3 hours of advanced seminar (Physics 500) or graded problems (Physics 552/EECE 551) or graded research (Physics 650/EECE 651) - and at least 2 of those hours must be in Optics. No more than 6 hours of 400-level Physics/EECE coursework (excluding those that are cross-listed) is acceptable toward the degree.

Under Plan II-b (internship/course-based), a minimum of 33 hours of coursework, including 3 hours of Internship (PHYSCS / EECE 559), is required. This plan requires an industrial or a national/federal lab internship that lasts from six to twelve months. Students must interview with participating industry or lab representatives (under the guidance of a faculty representative or liaison) and arrange an appropriate internship. Quarterly progress reports, as well as a comprehensive final report, must be submitted by the student to a committee consisting of the faculty liaison, one other member of the Optics faculty, and the student's industrial or lab contact/supervisor. Internships would follow typical coursework plans in the first 12 to 18 months after the student has been admitted to the graduate program.
A. Mandatory Courses

- Advanced Optics I (Physics 463 or EECE 464)
- Advanced Optics II (Physics 554 or EECE 567)
- Laser Physics I (Physics 464 or EECE 464)
- Optics Lab (Physics 476L or 477L)
- Electrodynamics (Physics 511 or EECE 561)
- Guided Wave Optics (EECE 564) or Optical Fiber Communication (EECE 565)

B. Optional Courses

- Introduction to Optoelectronics (EECE 475)
- Quantum Mechanics I (Physics 521)
- Microelectronics Processing Lab (EECE 574L)
- Nonlinear Optics (Physics 555 or EECE 568)
- Solid State Physics (Physics 529) or Semiconductor Properties (EECE 572)
- Topics in Modern Optics (Physics 569) or Special Topics (EECE 595)
- Laser Physics II (Physics 564)
- Semiconductor Lasers and LEDs (EECE 577)
- Quantum Optics (Physics 566)
- Atomic and Molecular Structure (Physics 531)
- Optical Coherence Theory (Physics 556)

12 hours of coursework must be taken at 500 level or higher. Students in Plans I and IIb must submit and defend a thesis (Ia) or internship report (IIb). Students in Plan Iia must pass an oral exam. Students in Plans Iia or IIb can take at most 6 hrs of 400 level courses excluding those that are cross-listed (EECE and Physics).

6.1.1. M.S. Oral Exam:

3 committee members (two from the home department, one from the other department) are selected by the student to test the subjects covered in the core courses (Advanced Optics I and II, Laser I). The student has two attempts to pass the exam. The second exam must be taken between 3 and 12 months after the first attempt.

7. New Mexico educational ladder

The MS program introduced in 2002 is an important component of the emerging comprehensive educational infrastructure in NM that in recent years has been largely shaped by the burgeoning optics and photonics industry. The educational ladder, the focus of much recent local and national press coverage [Guenther 2002], [Pedrotti 2002], [Prasad 2003] has its roots at the middle school level, where students are being groomed to become a part of the newly established Photonics Academy at the West Mesa High School. The two-year Academy is a highly promising experiment funded by the Sandia National Laboratory to prepare a pool of high school graduates who will choose photonics-based microelectronics as a career. The TVI photonics program, alluded to earlier and the second major rung of the ladder, will be a natural choice for many of these Academy graduates, the rest likely preferring to apply to four-year B.S. programs specializing in optics. Efforts are currently under way to establish a B.S. degree in Optical Science and Engineering at UNM. Such a program, if and when it becomes available, will not only furnish a useful career option to many high school students of NM but also complete the local ladder of educational programs beginning at the mid-school level and finishing at the M.S. and Ph.D. programs at UNM. By its multiple entry and exits points, the ladder empowers the aspiring students to evaluate and determine their career goals and objectives.

8. WICHE affiliation

In 1996, after a critical review, the optics program at UNM was selected as a regional educational and research resource for the western United States, becoming a Western Regional Graduate Program (WRGP) under the auspices of the Western Interstate Commission on Higher Education (WICHE). Only about a hundred programs spread over all specialties have attained this distinction throughout the fourteen states under the WICHE umbrella. An important practical benefit of this special status is that qualified residents of any of these states may enter any of the WRGP programs at the resident tuition rate.
9. Conclusions

The University of New Mexico is celebrating the 20\textsuperscript{th} anniversary of its graduate programs in optical science and engineering. The academic program is supported by more than twenty graduate courses in optics, engineering, and optoelectronics that are offered on a regular basis.

Optics research at UNM has acquired an international reputation over the last decade, ranking consistently third in terms of papers presented at CLEO/QELS conferences. (Conference on Lasers and Electro-Optics/Conference on Quantum Electronics and Laser Science) pioneering work has originated from this program. Areas ranging from the quantum theory of laser, squeezed states, correlated emission lasers, atom cooling and trapping, and let to practical applications such as surface emitting semiconductors lasers, new material developments (thin films) for nonlinear optics, ultra-short pulse physics, and new concepts of laser gyro, to cite only a few recent examples.

In many areas, such as imaging and beam propagation, our research programs cover all steps from the theoretical and laboratory conceptual evaluation to the implementation with high-energy lasers. Such research has impact in pollution monitoring, communication, and astronomy. New techniques of optical microscopy have revealed sub-wavelength cellular structures embedded in highly diffusive materials. Very high field physics is being investigated with power lasers, leading for instance to multiphoton ionization, plasma generation and triggering of discharges.

10. Acknowledgements

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11. References


The experience and teaching innovations in education at the Universities of Siberia

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Abstract: The experience of joint work of Tomsk and Novosibirsk academic institutes and universities on the education of students and professional training of young specialists for scientific and industrial enterprises is generalized.
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1. Introduction
There is a proverb: "every cook praises his own broth". And in the well-known years of the Soviet Experiment, we resembled such a cook. This happened not because of our snobbery, but due to the absence of objective information about the situation in other countries. Now, we have a new “informational” situation, and there appeared an opportunity of contacts. We wish to get acquainted with the experience and innovations of our colleagues from other countries. We would also like to inform our colleagues about our own experience. Of course, one cannot do without the discussion of problems and shortcomings. This is especially important in the modern conditions of developing integration of the world science and high professional mobility of specialists.

I shall not go deep into general conceptual questions of the educational system in Russia. I will consider mainly those questions that concern directly the training of students, the professional training of specialists in the fields of optics, photonics, laser engineering, and technologies.

At the present time, we experience a change in the public formation. The political, economic, and social situations have changed abruptly. In all spheres of management, ideas of reformation are actively put forward. Unfortunately, this process is not always for the better. Our education system did not avoid this. Therefore, they say, it is important not to "throw the baby out with the bath water". It is necessary to choose and leave all the best that was accumulated in the previous period, and to develop new innovation solutions for the new situation. This is especially important, because sometimes it happens so that the new is simply a long-forgotten old.

2. “Phystech-System” in Siberia
For simplicity, let "before" denote the previous pre-reform period and "now" the present-day period. I know what it feels like in such periods, and I experienced this both in Tomsk and Novosibirsk. Both cities are rather important in Russia as large centers of education and science. Tomsk, with a history of more than four hundred years, has the first Siberian university. In more than a hundred years, Tomsk University became one of the leading universities of Russia, the basic highly professional educational establishment among other Siberian universities. Therefore, it is a place where specialists for the creation of new equipment and technologies for scientific and industrial enterprises are prepared. In 1969, the development of a Tomsk Scientific Center of the Siberian Branch of Russian Academy of Sciences begins in it.

Novosibirsk is a young city. Nowadays, however, it is one of the largest Russian centers of science, where there is the Siberian Branch of Russian Academy of Sciences, some large industrial enterprises, and 16 higher educational institutions, including two universities. They include Novosibirsk State University (NSU), a classical university of the Siberian Branch of Russian Academy of Sciences and Novosibirsk State Technical University (NSTU).

The so-called “Phystech-System” was an effective innovation solution in the field of education. It was realized for the first time in early 50ies, at the creation of a higher educational establishment of a new type, namely, the Moscow Physics-Technical Institute. Its basic principles are as follows:

- Search for potentially talented schoolchildren and their selection owing to the available system of internal and extra-mural physical and mathematical Olympiads and physical-mathematical summer schools.
- Active (both economic and ideological) support of the state to motivate young people for education and professional work in the scientific-technical sphere.
- Involvement of outstanding scientists and engineers for delivering lectures.
• Professional training of students through their direct participation in the work of leading scientific and technical teams in academic institutions and industrial enterprises. Their active work in creative laboratories headed by world-famous scientists and engineers.
• Atmosphere of creative competitiveness owing to the participation in scientific seminars, discussions, and conferences.
• Allocation of money for new scientific equipment for teaching laboratories.
• Guarantee of prestigious, well-paid (for our country’s conditions) jobs.

First, of course, this was made, as an exception, only for Moscow. Some elements of this system were used in other places, in particular, in Leningrad (now called St.-Petersburg). In large universities of Siberia, such as Tomsk and Novosibirsk, considered below, this system was developed further.

Alongside with a free inflow of students entering the university after passing entrance examinations, the universities search for and select talented young people - school graduates. For this purpose, there exists a system of Olympiads and specialized physical and mathematical schools (see Fig.1).

![Fig. 1. Scheme for student selection.](image1)

Certain scientific - educational complexes were formed. Their structure is presented in Fig. 2.

![Fig. 1. Structure of university relations of Tomsk and Novosibirsk](image2)

The Tomsk State University, which is third in Russia now, first developed in accordance with the same principles and, maybe in some respects, anticipated the ideas of the Moscow “Phystech”. Large scientific research institutes were created on the basis of the Tomsk University, who former graduates, became researchers of these institutes. The first of them was the Siberian Physics-technical Institute, which played an important role in the
The university also played an important role in the development of other large higher educational establishments in Tomsk, such as Polytechnical Institute (University), the Academy (University) of Control Systems and Radio-electronics, and some large industrial enterprises. In the 70es, the Tomsk Scientific Center of the Siberian Branch of Academy of Sciences was created. All this contributed to the organization of an effective training-scientific educational process [1].

Another interesting and important peculiarity of Tomsk is a unique atmosphere of the Students’ Quarter. It facilitated a specific openness of scientific teams and personal relations between scientists and students. In 1961, a Chair of Optical Electronic Devices and Laser Physics was open. I was happened to be among its first graduates. Our young specialists worked at the first institute of the Academy of Sciences in Tomsk, the Institute of Atmospheric Optics, after its opening in 1969. The main directions of research of the Institute were investigation of the propagation of laser radiation in the atmosphere, laser spectroscopy, and problems of remote laser sounding of the atmosphere. The absence of dropout because of academic failure was a feature typical for those years.

The Novosibirsk Classical University was created directly in the structure of the Siberian Branch of Academy of Sciences, which was the initial place of work of many graduates of the Tomsk University and Moscow PhysTech. Therefore, the same concept of training as a unified educational-scientific process was used in the educational system of Novosibirsk higher educational establishments. Undergraduates, beginning with their third year of learning, become probationers - researchers at laboratories of academic institutes and get wages for their job. They participate in research projects, scientific seminars, and conferences.

The years of social and political restructuring (“perestroika”) in Russia since 1985, have changed essentially the social conditions and priorities. Industrial depression, a low living standard, low wages, and a lot of new temptations of carefree life changed essentially the motivation of young people associated with the professional orientation to the sphere of science and engineering. Many highly qualified professors left the educational system. There was no more money for new equipment and devices for university teaching laboratories. Only unique scientific setups in academic institutes were kept at the up-to-date level. There still remained, however, the traditions of selfless work of scientists with students. As before, institutes provide its unique equipment for its joint use by teachers and students.

The scientific community always expresses its anxiety about this situation and, at last, it succeeded in getting a governmental decision on a long-term state program of financial support of a new educational concept based on the integration between the educational process and scientific research and development. The program called "Integration", although it gets small financial support, allows us to maintain a unique microclimate of a unified training-scientific "university - academy" medium. Institute of Laser Physics and Institute of Nuclear Physics, SB RAS, are basic institutes for the Physical-Technical Faculty of Novosibirsk Technical University (NSTU) and for the NSU Physical Faculty. Now, most leading specialists of these institutes are graduates of these faculties.

For instance, the following fact shows that the idea of "Integration" is useful. Since the situation with professions and social priorities has changed, there are many poorly prepared school graduates with poor motivation for study in physical and technical specialties. Regrettably, their only aim is to prolong the period of carefree life or avoid going to the army, since army service in Russia is not prestigious.

We do not reduce the requirements to the results of studies, and therefore many students (up to 40 %) have to leave the university after the first year of studies because of their poor results. Others, after visits to academic institutes, meetings with leading scientists, participation in scientific research, and first successes, change their motivation abruptly. In fact, each student has an individual scientific supervisor. The creative atmosphere of scientific laboratories "captivates" these students, and they are willingly dive into it. Although there are less than 3% of people studying at the Physical-Technical Faculty of the NSTU, they always constitute a stable 30% proportion of prize-winners from the total number of all participants of Scientific Students’ Conferences [2].

The reorganization caused one more distressing factor. Some young people became less responsive to pedagogical measures, personal relations became more complicated, and the attitude to the university property, devices, and equipment was no longer careful. Unfortunately, the ideas of freedom are often understood as permissiveness. I do not know whether we are right or not by assuming that the pedagogical component should also remain an immutable factor in relations with students during their university study. At the age of 18, there are a lot of ambitions, but the personality is not yet formed. Young people yield to the temptation of street freedom, sometimes with harmful consequences.
The inevitable need to adapt to the new economic situation and market relations resulted in one more contradictory situation in the field of education: the professors and teachers, as well as the university management naturally wish to maintain their professional level in science and the university prestige. For this, teaching and research laboratories need expensive modern equipment. To prepare a good specialist, provide a young man with a good social guide, highly qualified teachers and a certain infrastructure (library, gym, special recreation services, etc.) are required.

Only large universities can have a high-level infrastructure, highly qualified teachers, devices and equipment necessary for the educational process, and all other indispensable things. Nevertheless, the Ministry of Education, which does not have enough money, put forward and actively supports the idea of financing from the budget of the region, in which the university is located. Then some regional administration heads (they have no money either, and this can be understood) declared that they do not need large universities at their territory. This position is, of course, short-sighted, but we hope that these views will not prevail.

In this problem, however, there is certainly also a progressive element. Universities should make better use of their intellectual resource for innovation decisions to solve social-economic problems of regions, fundamental innovation positive changes in the technologies and social life of the society as a whole. Now, at last, large city enterprises have again begun to form special orders for young specialists in the production sphere. This inspires of optimism.

We have opened the first Student Branch of SPIE (Novosibirsk SPIE Student Chapter) in Russia, for which I would like to thank the SPIE management. This has opened up new interesting opportunities for students, and they can get access to scientific magazines and new information. In summary, I would like to note that we have both "troubles" and "victories", which are outlined in Table 1.

<table>
<thead>
<tr>
<th>BEFORE (a characteristic feature)</th>
<th>NOW (for the time being!)</th>
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</thead>
<tbody>
<tr>
<td><strong>Social-economic situation:</strong></td>
<td></td>
</tr>
<tr>
<td>- Free education at all levels</td>
<td>- Mixed education system (free and paid)</td>
</tr>
<tr>
<td>- High motivation to learning new engineering and technology specialties (basis: high social prestige of professions)</td>
<td>- Decreased motivation to learning engineering and technology specialties (basis: low prestige of professions)</td>
</tr>
<tr>
<td>- Social safety of students’ life; optimism; absence of aggression in personal relations, benevolence; susceptibility to pedagogical measures, consciousness; guaranteed employment (state orders)</td>
<td>- Difficult social conditions of students’ life</td>
</tr>
<tr>
<td></td>
<td>- Devaluation of human values, problems in personal relations</td>
</tr>
<tr>
<td><strong>Main educational technologies:</strong></td>
<td></td>
</tr>
<tr>
<td>- Auditor lessons (lectures, laboratory works, practical lessons, seminars)</td>
<td>- Auditor lessons (lectures, laboratory works, practical lessons, seminars)</td>
</tr>
<tr>
<td>- Visits of enterprises, industrial and pre-diploma practice</td>
<td>- Computer technologies, possibility of remote education (under development)</td>
</tr>
<tr>
<td></td>
<td>- Integration of the educational process and works in professional scientific and technical teams (beginning with the second part of learning)</td>
</tr>
<tr>
<td><strong>Main shortcomings:</strong></td>
<td></td>
</tr>
<tr>
<td>- Non-openness to the outside world</td>
<td>- Insufficient number of the new textbooks and monographs</td>
</tr>
</tbody>
</table>

3. References

Optics related courses in Research and Educational Center "Plasma" at Petrozavodsk State University

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Abstract: The educational and research facilities in optics provided by the Research and educational center "Plasma" are described. Students study traditional, laser and correlation spectroscopy; interference and holography; image processing; nonlinear optics as well as methods of automated optical data acquisition and processing. The main attention in lectures, laboratory training and student's individual research works is attracted to optical methods applied to plasma diagnostics.

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Introduction

The research and educational center on basic problems of application of low temperature plasma physics (REC-013 "Plasma", Petrozavodsk, Russia) was found in 2002 within the project supported by the US Civilian Research and Development Foundation, Ministry of Education of Russian Federation and government of Republic of Karelia.

This project consists mainly of the development of experimental and theoretical investigations in the field of atomic and molecular physics, low temperature plasma physics and relevant basic applications. The main attention is attracted to interconnection between fundamental properties of "new" objects of atomic and molecular physics and low temperature plasma physics on the one hand and behavior of these objects in operating conditions of practically important devices on the other hand. Term "new" objects stands for complex ions, Rydberg atoms and molecules, clusters, fullerenes, nanotubes, plasma crystals. Experimental investigations of physical and chemical properties of these objects as well as mechanisms of their formation and destroy in low temperature plasma conditions are connected with the development and modification of beam, optical, radio-frequency and X-ray methods of control and diagnostics of plasma media with use of modern laser techniques, spectral analytical setups and modem vacuum and cryogenic equipment and involve the computer processing of measured data. The results of the investigations are supposed to be used in exploration and development of new knowledge in theoretical physics, micro- and nanoelectronics, and also for design of new types of electronic devices and plasma technologies.

The majority of modern ways of control of conditions and characteristics of plasma objects and results of interaction of plasma with substance is based on analysis of spectral and spatial distribution of radiation, emitted, absorbed or scattered by object of investigation. Undertaking of such studies requires high professionalism and high level of experimental technology and installations. Training specialists on optical and x-ray diagnostics and control of characteristics, conditions and structures of materials and substances is traditionally carried out at physical technical faculty. REC "Plasma", from the one hand, formulates problem-oriented tasks for these specialists and, from another, provides new instrumentatation and new abilities in methods development. In addition to geometric and physical optics which are included in course of basic physics, the theoretical basis of training in the sphere of optics is establishing in course of quantum physics, where significant attention is attracted to the questions of theory of atomic spectra, forming spectral lines shapes, especially in plasma conditions, as well as to the questions of quantum optics, including photon statistics, interference of quantum states and interference of intensities. One of the courses in training program is laser physics. Also applications of optical methods to plasma diagnostics resulted in special course supported by laboratory classes. For practical application of basic knowledge formed by these theoretical courses there have been introduced a special set of laboratory educational-research programs connected with certain studied problems.

1. Optical methods of plasma diagnostics

The purpose of this course and accompanying it laboratory practical programs – not only to arm the student by instruments and facilities of plasma diagnostics, but also to maintain and to teach to apply in practice fundamental knowledge, obtained at study of wave and geometric optics, quantum and laser physics, math basis.

Preamble part of course describes the well-known models of plasma (for instance, model of full or local thermodynamic balance, kinetic model) and shows the parameters to be determined and experiments that can
confirm or disprove validity of these models. After that a general scheme of diagnostics is stated, in which it is shown that any method of diagnostics can be introduced, only if the following parameters and factors are known.

1. A physical model linking required local and instant values of parameters of plasma in a certain elementary volume (densities of electrons \( N_e \), ions \( N_i \), atoms and molecules of different sorts both in ground \( N_g \) and excited states \( N^*_e \), electronic \( T_e \) and atomic \( T_a \) temperatures and electric field intensity \( E \)) with optical parameters of elementary volume: radiation \( \varepsilon(\lambda) \) and absorption \( k(\lambda) \) factors in spectral lines and continuous spectrum, refractive index \( n(\lambda) \), as well as differential cross section of scattering \( \sigma(\lambda) \) depending on wavelength and integral characteristics of radiation \( I \) and absorption \( K \) in spectral lines. In case of plasma with macroparticles, their contribution to the characteristics mentioned above should be taken into consideration apart.

2. A source model allowing to interconnect the optical features of source (plasma object): spectral energy radiance of source surface \( b(\lambda) \), optical thickness \( \tau(\lambda) \), portion of falling radiation \( P(\theta, \lambda) \), scattered in a certain angle \( \theta \) to the direction of radiation propagation, phase difference of incoming wave \( \Phi(\lambda) \) or deflection of beam from initial direction \( \alpha \) at passing through plasma with characteristics of elementary volumes. (The simplest interconnection of these parameters is in case of homogeneous source, more complicated – for axial symmetric heterogeneous source and even more complicated – for free type of heterogeneity. These problems are discussed in corresponding to sections of course.)

3. A project for laboratory equipment, providing conversion of optical characteristics to data array of registering system.

On the basis of chosen physical models and data acquired in experiment a researcher carries out the conversion of data array to spatial-temporal distribution of required plasma parameters. It is called as "inverse problem", whose solution can be unstable due to experimental inaccuracy. The way of overcoming these difficulties is considered in special section of course.

Section "Spectroscopic methods of diagnostics of plasma" is devoted firstly to the classical theory of interconnection of integral intensity of spectral lines and integral absorption with quantum states population and secondly to relation of intensity of continuous spectrum background with electron density and temperature \([1, 2]\). The theory of spectral line broadening as well as conditions under which different broadening factors can be considered as independent are studied \([3]\). Then the resulting line shape is a convolution of profiles, defined by various reasons. If all broadening factors except one may be neglected then basing on the form of profile it can be determined either atomic temperature (Doppler broadening) or electron density (Stark broadening) or ground state atoms density (resonant or Van-der-Waals broadening). In case of joint influence of several broadening factors their contribution can be separated if they lead to different dependencies of radiation factors on wavelength. For instance, if Doppler line shape is

\[
\varphi_{D}(\lambda) = A \cdot \exp[-\beta(\lambda - \lambda_{0})^{2}], \quad \beta = c^{2} M/(2 \chi \lambda_{0} T_{a}),
\]

(1)

where \( c \) – light velocity, \( M \) – mole mass, \( \chi \) is the Boltzmann constant, \( \lambda_{0} \) – spectral line center, and resonance line shape is \([3]\)

\[
\varphi_{R}(\lambda) = B/(\lambda - \lambda_{0})^{2 + \gamma^{2}}, \quad \gamma = \lambda_{0}^{2} \lambda_{R} e^{2 f N_{a}(g_{0}/g_{a})^{1/2}}/(4\pi c^{2}),
\]

(2)

where \( m, e \) – electron's mass and charge, \( \lambda_{R} \), \( f \) – wavelength and strength of oscillator of transition, connecting one of states of this line with ground state, \( g_{a} \) – stat. weight of this level, \( g_{0} \) – stat. weight of ground state, then according to convolution theorem:

\[
F(\omega) = \Phi\{\varphi(\lambda)\} = \sqrt{2\pi} \Phi\{\varphi_{D}(\lambda)\} \cdot \Phi\{\varphi_{R}(\lambda)\},
\]

(3)

where \( \varphi(\lambda) \) is the resulting line shape and \( \Phi \) is Fourier transform operator. In our case

\[
\ln(F) = - \alpha^{2}/(4\beta) - \gamma|\omega| + C
\]

(4)

A, B, C in equations 1, 2, 4 – unimportant constants. From the system of equations (4) values of \( \beta \) and \( \gamma \) may be found by root mean square method for several values of \( \omega \).

Type of line shape, integral intensity and absorption factor can be easily calculated from values of radiance of source surface and optical thickness only in case of homogeneous source. In other cases these characteristics must be determined for different points of surface or for different directions of exposure; spatial distribution of the optical characteristics of elementary volumes is derived by means of solving corresponding integral equations. Anyway spectral distribution of radiance of surfaces and optical thickness in one or several spatial points must be measured. Therefore main part in this course is devoted to special spectral instruments. For each type of these instruments (prism, diffraction and Fourier spectrometers, Fabry-Perot interferometers) there have been studied the factors, depending on working range and best resolution, i.e. on form and width of apparatus spread function. It is shown...
principle advantage of interferential instruments to slit apparatus in study of weak light sources. Few methods of realization of image spectrometer what is necessary in investigations of spatially heterogeneous sources are considered. Aside from trivial variants, containing different systems of spatial scanning, as well as optical fiber system, separating radiation from different parts of the source on different spectral nodes, modern, often of original design, devices based on multiple-unit photodetectors (CCD arrays and matrices) are described.

To investigate one-dimensional distribution of radiances it is possible to use a slit spectrometer with photosensitive matrix. Direction of change in radiance should correspond to the axis of slit and to columns of matrix, each line of matrix will register the spectrum of a certain spatial element.

At study of objects with "rare" line spectrum good result can be given by well known in astronomy slitless spectrometer. Placing an investigated object or its image at the entry of usual prism or diffractional spectrometer instead of input slot (fig. 1), the picture of object in light of different wavelengths will be registered at the output of this instrument. The condition of "no superposition" of different spectral images is:

\[ \Delta \lambda_{\text{min}} > t \left( \frac{d\lambda}{dx} \right), \]  

where \( \Delta \lambda_{\text{min}} \) – minimal spectral distance between lines, \( t \) – size of object in the direction of dispersion of instrument, \( d\lambda/dx \) – its inverse linear dispersion.

\( \lambda_1 \quad \lambda_2 \quad \lambda_3 \)

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<th>I</th>
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<th>D</th>
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Fig. 1. Slitless spectrometer. S - source, L - lens, D - diffraction grating, P - output plane with picture of object in various wavelengths, I - fine interferometer, which is used in investigations with continuous spectrum.

This method may also be applied to study spatial distribution of radiances in different ranges of continuous spectrum. To implement this it is necessary to "thin out" the whole spectrum beforehand, i.e. to transform it in line structure with an interval between "lines" of \( \Delta \lambda \). It may be done by passing radiation through fine interferometer Fabry-Perot. Students are to calculate the system for registration of spatial distribution of radiance of an object of given size with given spectral step \( \Delta \lambda \), they must choose the thickness \( d \) of the interferometer, and also parameters of grating and focal length of lens. However it should be taken into consideration that picture of object in image plane will be blurred a little. This image blurring is determined by the passband spectral width of a filter and by dispersion of grating, nevertheless achieved in the above mentioned way spatial resolution (approximately 30 elements per width of object) as a rule is enough for practical purposes.

For stationary in time or slowly changing objects the best variant of image spectrometer can be built on the basis of interference spectrometer (Fabry-Perot with filter of preliminary monochromatization or Fourier spectrometer), since such a system combines a source image with interference rings pattern on output (fig. 2). In this case spectrum scanning is realized by means of change of optical width (base) of interferometer, and spatial resolution is limited only by quantization of matrices and is practically well enough. Here the difference between optical paths of two waves in interferometer (axial and propagating at the angle \( \delta \phi \) to it) may be neglected if the following condition is fulfilled:

\[ \delta \phi \leq (2\delta \lambda_0/\lambda)^{1/2}, \]  

where \( \delta \lambda_0 \) – spectral width of spread function of spectrometer.
Fig. 2. a). Installation with Fabry-Perot interferometer (I). S – source, P – imaging plane, L₁, L₂ – lenses; b). Interference pattern in P plane.

For example, it is possible to obtain spatial spectrum distribution on the object of 1 cm size using Fourier spectrometer with \( \delta \lambda_a = 1 \) nm and drawing lens with focal length of 30 cm. For objects of large angular sizes also there are no principle difficulties. It should only be taken into account in case of processing interferograms that for points of interference pattern, distanced from the axis of system on angle \( \phi \), difference in optical paths is \( \Delta = \Delta_0 \cos \phi \), what is less, than \( \Delta_0 \) – difference of optical paths along the axis of system.

Since photosensitive matrices are essential elements of image spectrometer, metrological features of different types of matrices: spectral sensitivity, range of linearity, noise level, deviation of sensitivity of different elements, are researched by students within the framework of laboratory educational-research programs.

The study of spectral instruments is terminated by a section, dedicated to spectroscopy of high resolution, i.e. resolution, not achievable by the most exact optical spectral instruments. Small differences in radiation frequencies and small line widths corresponding to radio frequency range may be measured by methods of optical heterodyning or methods of correlation spectroscopy (interference of intensities) [4]. The method of optical heterodyning can easily be explained in common terms of summation of coherent waves and by the following concept: photo sensor is a square-law detector. The phenomenon of interference of intensities (correlation spectroscopy) can be understood either on the basis of knowledge got in course of quantum physicists about Bose-Einstein statistics, which comply with the photons, or on the basis of classical wave theory of light in suggestion that observed radiation is a result of superposition of waves, emitted by independent sources. Each of these waves can be described by complex function, intensity is proportional to the square of module of this function and has a random nature; correlation function for two spatial-temporal points depends on degree of coherence of fields in these points. It is shown that both approaches lead to similar results. The study of this subject fastens the fundamental knowledge on physical optics and probability theory. Since radiation spectrum is a Fourier image of degree of coherence the information on spectral lines widths can be obtained from correlations intensity function. As an application to problems solving in REC "Plasma" this method is used for measurement of diffusion coefficient of dust particles in glow discharge plasma. These measurements are considered to be an imperative step of investigations of mechanisms of forming ordered structures in dust plasma [5]. On fig. 3 one of the results of work carried out with participation of student and reported at conference on Physics of Low Temperature Plasma (PLTP-03) [6] is presented.

Calculation were done using this formula:

\[
G = \frac{g(\tau) - g(\infty)}{g(0) - g(\infty)} = \exp(-2q^2D\tau),
\]

where \( g(\tau) \) – correlation function of intensity of scattered light, \( D \) – diffusion coefficient, \( q \) – wave number \( q = (2\pi/\lambda)\sin(\beta/2) \), \( \beta \) – angle of scattering, in our case \( \beta = 90^\circ \). It is obvious that experimental curve corresponds well enough to calculated curve with \( D = 7.5 \times 10^{-8} \) cm²s⁻¹.

The spectroscopic methods of Doppler-free broadening also belong to methods of high-resolution spectroscopy. These methods allow distinguishing the broadening taking place due to interaction with charged or neutral particles in plasma and to determine their densities even if this interaction caused broadening is less than Doppler effect. In the discussed course methods of two photon spectroscopy and interference of states of atom are studied.
The section "Spectroscopic methods of plasma diagnostics" is terminated by the description of characteristics of photo sensors (quantum efficiency, noise level and nature of noises), analysis of factors, limiting sensitivity, spectral, temporal resolution of spectroscopic installations and also by the description of methods of measurement of absolute values of radiance of surface and optical thickness of source. There have been considered both simplest methods: illumination by tunable laser, by source of continuous spectrum and its own radiation, and well-known more sensitive methods: laser fluorescence [7] and intra resonator spectroscopy [8].

In section "diagnostics based on refractive index" the interconnection of refractive index with density of atoms and electrons in elementary volume of plasma is determined on the basis of classical theory of dispersion. Two boundary conditions are considered: 1) wavelength of probe (input) radiation is close to wavelength of an absorption line of atoms or ions presenting in plasma, 2) wavelength is far enough from all lines of atoms and ions.

In first case the density of atoms on absorbing level can be measured by methods of polarization spectroscopy. At illuminating plasma by radiation with frequency $\omega$, close to absorption frequency $\omega_0$ of one of the plasma component, refractive index is described by formula:

$$n_1 - 1 = \frac{q N \Delta \omega}{2 \omega (\Delta \omega^2 + \gamma^2 / 4)},$$

where $\Delta \omega = \omega_0 - \omega$, $N$ – density of atoms on absorbing level, $\gamma$ – spectral width of absorption line (disregarding Doppler broadening). $q = \frac{e^2}{2\epsilon_0 \mu}$ ($\epsilon_0$ – dielectric constant of vacuum).

If place is put in magnetic field, which direction matches the direction of propagation of plane-polarized wave with frequency $\omega$, then after passing through plasma polarization plane will be turned from initial direction on a certain angle $\varphi$. This occurs due to effect of line splitting. In strong magnetic field one absorption line splits it two with frequencies $\omega_0 + \omega_B$ and $\omega_0 - \omega_B$, where $\omega_B$ – Zeeman splitting frequency, proportional to the induction of magnetic field B. Herewith plane-polarized wave with frequency $\omega$ transforms in two circularly polarized waves, propagating with different velocities. Difference in refractive indexes for these waves will be $\Delta n$. It's clear that this value depends on magnetic field. It is small in case of both tiny and large splitting because at large spectral distances from $\omega_0$ refractive index is practically equal 1. This phenomenon is used in different variants of the method. For example in one of the variants maximum value of angle shift is measured. This value, as it was stated in work of W.R. Bennet [9], is unambiguously connected with absorption coefficient in the center of line $k(\omega_0)$, and, consequently, with population of a level:

$$\beta = -0.28 k(\omega_0) L \sin \frac{\omega_0 - \omega}{0.3 \Delta \omega_D},$$

$$\Delta \omega = \omega_0 - \omega,$$

$$\omega_0$$ - absorption frequency.

$$\omega$$ - frequency of illuminating radiation.

$$
\begin{align*}
G &= \frac{g(\sigma, \omega) \cdot g(\omega)}{g(\omega_0, \omega)} \\
D &= 7.5 \times 10^{-9} \text{cm}^2 / \text{c}
\end{align*}
$$
where \( L \) – length of optical path of beam in plasma, \( \Delta \omega_0 \) – Doppler line width. By "waving" polarization plane of illuminating laser and determination of wave of the frequency of intensity modulation and polarized perpendicular to initial laser light, it is possible to measure the tilt of polarization plane for the angle less than 10° radian, what allows to register the density of absorbing atoms down to \( 10^6 \) cm\(^{-3} \) in conditions of 1 cm optical path length and Doppler width of order of \( 10^9 \) s\(^{-1} \) [10].

The second variant of polarization spectroscopy [11] assumes the work on lines with large absorption on frequencies \( \omega_0 \), distanced from the center of line \( \omega_0 \) farther than Doppler width. Plasma located in magnetic field is illuminated by polarized tunable laser radiation with \( I_0 \) intensity. The intensity of light, initially polarized in perpendicular plane and passed through plasma, is registered:

\[
I = I_0 \exp[-\kappa(\omega_0)L] \sin^2 \varphi. \tag{10}
\]

The intensity as a function of frequency consists of two multiplicands, the first increases, but the second decreases with growth of \( \omega_\gamma - \omega_0 \). This dependence has its maximum, when \( \omega = \omega_\gamma - \omega_\text{max} \), what allows to find either the density of absorbing atoms \( N \) if \( \gamma \) is known, or linewidth \( \gamma \) if \( N \) is known.

At far spectral distances from absorption lines the refractive index of plasma is expressed as:

\[
n - 1 = q \sum_{ajk} N_{ajk} f_{ajk} \frac{\gamma N}{\omega^2}. \tag{11}
\]

The first summand contains the sum on particles of different sorts \( a \), existing in initial state \( j \), from which a transition is possible to any \( k \) state. However in practice only ground states of atoms and transitions with frequency \( \omega_{ajk} \) and oscillator force \( f_{ajk} \) are taken into consideration since these states have the largest densities. It should be mentioned that \( f_{ajk} \) are calculated by quantum mechanics methods and are tabulated for many transitions (for example in [12]). To distinguish the contributions of electrons and atoms in the refractive index few measurements on different wavelengths should be done.

The main method of measurement is interferometry. The difference in \( \theta \) (wave phase of the beam with wavelength \( \lambda \)) between two beams (passed a distance \( L \) through plasma and passed the same distance in medium with well known refractive index) is to be measured.

\[
\theta = \frac{2\pi L}{\lambda} \int_0^L \Delta n(z) dz \tag{12}
\]

In case of heterogeneous source such measurements are to be done for different directions of plasma probing. In tasks of diagnostics of plasma the most convenient methods are holographic interference methods since there is no need to take care of interference quality of plasma bordering surfaces and of tuning of interferometer. Students study the principles of holography, main methods of holographic interference: method of two exposures and method of "alive bands", allowing to dynamically observe changes of refractive index of nonstationary objects. As exercises they are offered to calculate the minimal densities of atoms and electrons, which are possible to measure by the holography method under given discharge geometry and noise level of a system, measuring intensity of interference pattern.

In section "diagnostics based on light scattering" there have been considered on the basis of classical electrodynamics the possibility of use of line shape of Thomson scattering on free electrons for study of electron velocities distribution functions, as well as criteria for applicability of this method are specified. If these criteria are not complied (at large electronic densities and small scattering angles), information on plasma parameters is contained in scattering spectrum in other form: combinational scattering on plasma fluctuations occurs. Frequency of fluctuations is connected with density and temperature of electrons. In this section principle of Coherent Anti-Stokes Raman Spectroscopy and its use for determination of populations of levels of atoms and molecules are considered also. Developing within the framework of REC direction of dust plasma studies has required introduction in the program of methods of dusty particles diagnostics by light scattering. In particular, in student's educational and research works different software realizations of theory of Mie were executed [13].

The common way of registering spatial distribution of heterogeneous plasma parameters basing on the integral characteristics of source (radiance of surface, optical thickness, phase difference) is to implement the tomography. So the study of the main terms of tomography (cross section and projection), mathematical basis of computer tomography (Radon's transform and Abel's transform as its private case), use of Fourier transformations in tomography and description of main methods of reconstruction of cross sections basing on projections are included in the program of this course. Some of these techniques are reviewed in training program on tomography, which is presented in another report entitled "The computer training program on tomography". These methods are also introduced in few student works. In particular in one of the diploma works tomographic interferometer was constructed [14], what in fact is an analog processor design. It realizes the method of inverse projection for
reconstruction of lines of equal refractive index, i.e. of equal density of atoms, basing on phase shifts of waves illuminating heterogeneous object from different directions (fig. 4).

Application of tomography to study of dusty plasma is described in the work, executed in collaboration with student and submitted to Northern Optics 2003 conferences [15].

A rational algorithm of data processing for wide-spread case of axial symmetric heterogeneous source is also in details considered in course [16,17].

For investigation of one section of cylindrically symmetric plasma the two-dimensional array of samples \( F(\lambda_i, x_j) \) corresponding to spectral surface radiance \( b(\lambda_i, x_j) \) have to be measured along a series of chords, perpendicular to plasma axis \( (x_j - \) the displacement of chord from plasma centerline, \( \lambda_i \) - wavelength of spectral point inside the profile). From the array \( b(\lambda_i, x_j) \) the array of spectral emissivities \( e(\lambda, r) \) has to be reconstructed and spectral line profiles \( e_j(\lambda) \) for distance \( r_j \) from the section center have to be found. These profiles may be used for the determination of plasma parameters in this spatial point. The reconstruction of emissivity \( e(r) \) from measured intensity \( b(x) \) is known as Abel’s inversion

\[
\varepsilon_r(x) = -\frac{1}{\pi} \frac{R_0}{r} \frac{dx}{\sqrt{(x^2 - r^2)}}.
\] (13)

Here \( R_0 \) is the discharge tube radius.

It is so called improperly posed problem and the solution is impossible without using of a priori information about function \( e(r) \). But measured line profiles \( F(\lambda_i, x_j) \) may be distorted by the spectrometer spread function.

\[
F_{out}(\lambda) = F_{in}(\lambda') \cdot g(\lambda - \lambda') d\lambda'.
\] (14)

\( g(\lambda) \) is the spectrometer spread function, \( F_{out} \) is the observed line profile, \( F_{in} \) is the true line shape and it is proportional to \( b(\lambda) \). The elimination of instrument distortion is possible, for example, by use of the convolution theorem [like equation (3)]. If \( g(\lambda) \) is known we simply have to divide Fourier transform of \( F_{out} \) by Fourier transform of \( g(\lambda) \) and then reconstruct \( F_{in} \) by the inverse Fourier transform of the result of division. But it is also an improperly stated problem, its solving is very sensitive to experimental data noises. The algorithm describe in this course significantly increases the results stability in the presence of experimental data noises, when it is necessary to solve both improperly stated problems concurrently. The algorithm is based on collective processing of large data arrays of sample data \( F(\lambda_i, x_k) \).

For the first step of algorithm one has to calculate the covariance matrix \( A \) of the array of profiles \( F(\lambda_i, x_k) = F_{ik} \), corresponding to one or, perhaps, several spectral lines and time points.

\[
A_{jk} = \frac{1}{n} \sum_{i=1}^{n} (F_{i,k} - \overline{F_k})(F_{i,j} - \overline{F_j}),
\] (15)

where \( n \) is a number of spectral points, \( \overline{F_k} = \frac{1}{n} \sum_{i=1}^{n} F_{i,k} \) is an average spatial vector.

Then the array \( F_{ik} \) may be described by a model:
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\[ F_{i,k} = \overline{F_k} + \sum_{p=1}^{q} M_{i,p} U_{p,k}, \]  
(16)

where \( U_p \) are eigenvectors of the covariance matrix \( A \) and \( M_{i,p} \) are the projections of \( i \)-th spectral point to eigenvector \( U_p \).

\[ M_{i,p} = \sum_{k=1}^{m} (F_{i,k} - \overline{F_k}) U_{p,k}, \]  
(17)

As a consequence of mutual dependence of elements \( F_{i,k} \) the number \( q \) of significant eigenvectors of \( A \) is less than \( m \). The eigenvector is significant if corresponding eigenvalue is no less than estimator \( S^2 \) of variance of experimental error. Before further processing one has to prove that model (5) with \( m(q+1)+qn \) coefficients is adequate. For this purpose the Fisher criterion has to be used [18].

The operations of radial transform (let us denote the corresponding operator \( R \)) and elimination of instrument distortion (let us denote the corresponding operator \( C \)) are linear and applied to different variables. So instead of the instrument distortion elimination from each profile \( F_i(\lambda) \), and then Abel's inversion for each wave length \( \lambda_i \); for the next steps of algorithm one can eliminate the instrument distortions from projection \( M_{i,p} \), then fulfill the radial transform for \( \overline{F} \) and \( U_p \) and restore the required profiles \( \varepsilon(\lambda_i,r_j) \) in various plasma points \( r \) as:

\[ \varepsilon(\lambda, r) = R \{ \overline{F} \} + \sum_{p=1}^{q} L_p(\lambda) R \{ U_p \}, \]
(18)

where \( L_p = C \{ M_{i,p} \} \) are the results of instrument distortion elimination from parts of projections \( M_{i,p} \), corresponding to each spectral line.

The spectroscopic method of determination of electric field strength in plasma is considered in the final section of course. This is very important in particular in investigations of dusty plasma, when using the standard probe method is impossible. At the moment two principles of using laser spectroscopy are offered to measure the local fields in plasma.

The First method is based on the measurement of Stark splitting higher atomic levels. In one variant using tunable laser the population of certain Stark sublevel of one of higher excited states is increased and the fact of increase is registered by means of optogalvanic effect – the discharge current growth due to increase of number of ionizations from this level [19]. In another variant [20] transition to Stark sublevel causes the reduction of population of lower level, the decrease corresponds to decrease of intensity on fluorescence lines from this devastated level.

The Second method is based on appearance of prohibited lines in spectra of atoms or molecules in the presence of external electric field since wave functions of states in external field are described by the superposition of different states and selection rules legal for fields of central symmetry are broken. Superposition coefficients are calculated by the solving appropriate Shrödinger's equation and the relationship of intensity of prohibited line with field strength is revealed [21]. This result has great cognitive importance, illustrating practical profit of quantum mechanics technique.

2. Laboratory programs on optics and spectroscopy

At study of course of general physics students execute the standard set of laboratory programs, illustrating the laws of geometric optics, phenomena of light interference, polarization, diffraction as well as optical pyrometry. In course of laser physics works on measurement of spectral composition, power and angular divergence of laser radiation are fulfilled. In course "Physical bases of reception of information" all students get acquainted with process of registering and recovering holograms and execute simple experiments on optical spatial filtration, in particular, installing and moving the "knife" in Fourier plane of a system, drawing image of an object, and visualize the defects in transparent objects, evaluate the sizes of heterogeneous areas in objects. These programs prepare the specialists to use the holographic and shadow methods of plasma diagnostics.

The majority of works in the scope of this course as well as of courses on atomic and quantum physics spectroscopy and plasma diagnostics are carried out with use of new information technologies and a possibility of remote access to the equipment. Students come to know a subject area (e.g. determination of fundamental atomic constants, Zeeman effect, plasma diagnostics, temperature determination, eliminating the apparatus distortions etc.) in parallel with acquiring habits in usage of modern information systems and effective methods of accumulation, processing and transformation of data. They are trained in usage of local and remote information resources and study the operation principles and possibilities of various measurement sensors [22].

Hardware and software for these laboratory programs are based on LabView and compatible instrument interfaces. It is built of separated modules and can be easily adapted for any set of the spectral equipment and any modern operational environment. Each module is made as a "virtual instrument", on the panel of which there are
windows for input of the necessary information, control buttons (start of the module, save file) and graphic field for result representation. Examples of such panels are given in figures 5, 6.

By processing the array presented in Fig. 7 using the above described algorithm students have to receive spectral line profiles $\varepsilon(\lambda_i)$ for different distances $r_j$ from the discharge center and to estimate electron or atom density at this point by spectral line width or shift [1].

For processing data presented in Fig. 8 students have to calculate the interferometer spread function:

$$ P(\beta) = \frac{(1 - R)^2}{(1 - R)^2 + 4R\sin^2 \pi\beta} $$

(19)
(β is the fraction of the distance between the nearby interference peaks, R - mirror reflectance) and to eliminate the instrument distortion by free accessed program [23].

It should be mentioned that almost all our spectroscopic installations allow the work in distributed research nets and provide remote access to information and physical equipment through Intranet/Internet channels.

The knowledge obtained in the discussed courses is also supported in special lecture and practical course "Automation of scientific research".

Besides studying basic subjects students can choose an optional course, for example, "Nonlinear optics" or "Optical processors". The latter is devoted to the principles of Fourier optics, their application to certain problems of processing and scene analysis, including the possibility of using spatial filtrations for spectrum decryption and exclusion of apparatus distortions [24], as well as to the principles of integral optics, acoustic optics, optical bistable and logical elements, realization of optical relationships in neurocomputers and matrix elements (optical programmable logic arrays). The principles and perspectives of quantum computers are considered. It spreads the horizon of students, makes the perception of new ideas in the theme field of REC "Plasma" easier (for example, recent propose to use optoacoustic filter as an element of image spectrometer) [25].

All students use web-based textbooks, learning software (e.g. "Fourier spectrometer", "Modeling and exclusion of apparatus distortion") and other web-resources published on site of department (http://dfe3300.karelia.ru/) and on REC's site (http://plasma.karelia.ru/). One of the subdivisions of the latter site contains lectures on plasma diagnostics read at summer schools on low temperature plasma physics and at scientific seminars of REC "Plasma".

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[26] L. Luizova, A.D. Khakhaev, V.P. Chugin, "Optical processors". The latter is devoted to the principles of Fourier optics, their application to certain problems of processing and scene analysis, including the possibility of using spatial filtrations for spectrum decryption and exclusion of apparatus distortions [24], as well as to the principles of integral optics, acoustic optics, optical bistable and logical elements, realization of optical relationships in neurocomputers and matrix elements (optical programmable logic arrays). The principles and perspectives of quantum computers are considered. It spreads the horizon of students, makes the perception of new ideas in the theme field of REC "Plasma" easier (for example, recent propose to use optoacoustic filter as an element of image spectrometer) [25].

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Skill Standards and Curricula for Photonics Technicians

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Abstract: Under funding from NSF’s ATE program, the national nonprofit R&D organization CORD recently developed and published the second edition of The National Photonics Skill Standards for Technicians (NPSST), which provides an employer-driven specification for the development of photonics education programs and supporting instructional materials, particularly at the two-year postsecondary level. This paper explains the need for NPSST and overviews its main components—specifications for what photonics technicians should know and be able to do in six broad photonics specialty areas, secondary and postsecondary curriculum outlines, a sample 4+2 photonics technology course sequence, and foundational knowledge components for two-year photonics technician programs.

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1. Introduction
Over the long haul, U.S. photonics industries face a critical need for more—and more highly skilled—technicians. Even with the recent downturn in the American economy, photonics technicians are in demand, and in future years that demand will significantly outpace growth in the pool of qualified candidates.

To be competitive in the workplace, and to grow as the field changes, photonics technicians need sophisticated technical skills and a strong foundation of academic and employability skills. But they do not necessarily need baccalaureate degrees. The skills required can be obtained through well-designed associate degree programs (especially if foundational programs at feeder high schools provide a “pipeline” for getting students interested in photonics and facilitating the transition to two-year postsecondary education). In fact, surveys show that many employers of technicians prefer graduates of two-year colleges to holders of bachelor’s degrees.

For these reasons technical and community colleges provide the ideal mechanisms for producing future generations of photonics technicians. However, for those institutions to provide the highly skilled technicians employers need, industry must collectively provide specifications, i.e., skill standards.

This paper focuses on the recently published second edition of the National Photonics Skill Standards for Technicians (NPSST) (CORD, 2003), which was developed through the National Science Foundation’s Advanced Technological Education program. In addition to briefly overviewing the evolution of NPSST, the paper describes the contents of NPSST in such a way that readers—especially employers, but also educators—will become aware of what they can do in their communities to improve dialogue between employers and community colleges, contribute to the development of educational materials and programs, and take other steps necessary to ensure that our nation’s photonics industries remain globally competitive long into the future.

A PDF of NPSST can be downloaded from http://utopia.cord.org/STEPPI/skills-pdf.htm.

2. A Challenge to the Photonics Community
The importance of the role of employers in the activities that NPSST is designed to facilitate cannot be overstated. Without the support of employers and information from them regarding what goes on in the workplace, educators and curriculum developers cannot adequately prepare technicians. At the same time, the participation of employers may require a broadening in their thinking about what constitutes the best possible training for technicians. For a variety of reasons (mainly financial), employers usually support programs that focus narrowly on the skills their organizations need. But one of the premises that NPSST reflects is that those same employers, along with every other stakeholder in the educational enterprise, derive greater benefit, over the long haul, from educational programs that provide foundations—academic as well as technical. When educational programs are too narrowly focused, local job markets may not be able to employ all of their graduates, leaving some young people without employment opportunities that enable them to make optimum use of their training. The skills provided through narrow job-training programs also tend to become outdated quickly.

Clearly, taking the long view—in which students are given the tools to grow and adapt over a period of years—is best, for employers and employees alike.
3. Background of NPSST

3.1 The first edition of NPSST and the STEP Project

In 1995, CORD released the first edition of NPSST, which represented input from 300 individuals from optics and photonics businesses and industries. The first edition identified the skills and knowledge required of workers and organized that knowledge into a generic program of study that could be emulated by community and technical colleges throughout the United States.

CORD subsequently served as a partner in an NSF ATE-sponsored project called STEP I (Scientific and Technological Education in Photonics), led by Chandra Roychoudhuri of the University of Connecticut. The objectives of that project were to develop ten postsecondary instructional modules based on the standards provided in the first (1995) edition of NPSST.

In 2003, as part of the second phase of the STEP project (STEP II), CORD began the task of producing a new edition of NPSST. Among the goals of the new edition (the focus of this paper) were (1) to make the skill standards consistent with recent developments in the workplace (which had undergone many changes during the six years since the first edition was published), (2) to provide a model for infusing pedagogical innovations and higher levels of academic content (especially math and science) into secondary and postsecondary technical curricula, and (3) to place stronger emphasis on the evaluation of skills (or behaviors) that technicians perform on the job so that the appropriate knowledge could be inferred and identified for educational programs. (The STEP II project is also revising the original curriculum modules; the revised versions will be pilot-tested at community colleges beginning in fall 2003. For more on the STEP II project, see http://utopia.cord.org/STEPII/. Co-PIs for the STEP II project are Arthur Guenther, University of New Mexico; Darrell Hull, CORD; Chandra Roychoudhuri, University of Connecticut; and Fred Seeber, Camden County College.)

3.2 Development of the New Standards

Developing the new standards involved several iterative steps that included staff interaction with business/industry representatives—first to ensure the appropriateness of the six specialty areas upon which NPSST is based (see “5. Organization of the Standards in NPSST”), and then to ensure that the scope for each was correct and inclusive to the degree possible. Field validation of the six specialty areas (along with their supporting “critical work functions,” tasks, and skills) was conducted via a dedicated, interactive website that enabled respondents to review and critique each critical work function, task, and skill online. Through the assistance of the two largest professional societies in the industry, the SPIE and The Optical Society of America, over 40,000 members of the industry were asked to review the standards and provide input. Of those contacted, over 200 responded. The information provided by the respondents was distilled and forwarded to six industry subcommittees (one for each of the six specialty areas), which reviewed field suggestions. Once input from business and industry members was complete, educators from two-year colleges and technical schools reviewed and validated individual knowledge requirements.

3.3 Addressing Mathematics Deficiencies

One of the tasks of the STEP II project is to address the mathematics deficiencies of students who attend two-year colleges. For this purpose, CORD developed a diagnostic instrument that can be used to identify mathematics deficiencies in areas in which students must become proficient to succeed as photonics technicians. CORD also developed a companion math review and study guide designed to help students, especially college freshmen, master the mathematics necessary to perform the exercises, labs, and problems in the introductory optics and photonics curriculum developed through the STEP project. (Both the diagnostic instrument and the review and study guide are available from CORD Communications, Inc. [800-231-3015], which also provides samplers at no cost.)

4. How NPSST Can Be Used

NPSST should be used as a guideline for developing and/or updating photonics education programs, especially at the two-year postsecondary level. (The document also provides information pertaining to articulated high school feeder programs.)

NPSST gives users a comprehensive view of what photonics technicians in certain broad specialty areas should know and be able to do—as determined by a consensus of over 200 practicing specialists in the field. Program developers (who should include both educators and employers) will find that the information provided eliminates the need for extensive research and thus gives them a head start on the development process.

NPSST’s curriculum resources (see “6. Curriculum Resources in NPSST”) are intended as a model, not a prescription for a canned curriculum. But they eliminate 85–90% of the work that most two-year colleges, working in partnership with local employers, would have to do to create or update their photonics curricula. The specialty...
areas addressed in NPSST provide starting points for almost any program. In many cases, colleges simply need to review and amend the standards to reflect local conditions, then review and amend their curricula accordingly.

The mission of every technical associate degree program should be to (1) provide skills that satisfy the needs of local employers, (2) prepare graduates for further education, and (3) give graduates mobility within the field and the ability to adapt as the field changes. To fulfill that mission, each program should represent a workable balance between the specificity desired by employers and the breadth desired by educators. NPSST is designed to help educators and employers find that balance.

The information provided in NPSST will also help school counselors gain an understanding of the photonics field that will enable them to describe the field’s rewards and demands to prospective photonics students.

5. Organization of the Standards in NPSST

NPSST divides photonics skill standards into six major specialty areas. The standards pertaining to each area are presented as a series of critical work functions. The description of each critical work function is accompanied by lists of relevant tasks, technical skills, and employability skills.

5.1 Specialty Areas

Photonics technicians work in the following six broad areas of specialization (which are the organizing principles upon which NPSST is based).

- **Communication**: Fiber optics, transmitters, and sensors
- **Lighting and illumination**: Lighting, displays, and entertainment
- **Medicine**: Biomedical optics and medical imaging
- **Manufacturing**: Materials processing, alignment, metrology, and inspection
- **Optoelectronics**: Nanotechnology, microsystems, and semiconductors
- **Imaging and remote sensing**: Signal and image processing, environmental, and aerospace

The six specialty areas should not be thought of as airtight categories. Rather, they reflect general groupings of the types of photonics-related activities that take place within a broad cross-section of the optics/photonics industry.

5.2 Critical Work Functions

In each of the six specialty areas, technicians are responsible for performing 4–6 critical work functions. Each critical work function is broad and subsumes a number of lower-level tasks. For example, one of the critical work functions for photonics technicians in the specialty area of Communication is:

*Assemble various fiber-optic components and modules into subsystems and understand their functions*

5.3 Tasks

Becoming proficient in each critical work function involves performing one or more of 5–10 tasks. For example, appropriate tasks for the critical “Assembly” work function identified above are:

1. Gather technical requirements for components/devices/materials to facilitate ordering and procurement
2. Assemble components/modules according to manufacturing specifications
3. Prepare component/module for final test
4. Perform reliability test and/or burn-in tests according to manufacturing specifications
5. Integrate fiber-optic components and modules into specified systems

5.4 Technical and Employability Skills

Performance of every task requires at least one skill (often several). In NPSST, the term skill refers to the basic abilities necessary to perform a given task. For any task, there may be significant overlap among the required skills. Further, there are two general classifications of skills:

- **Technical** (example: Measure noise equivalent power)
- **Employability** (example: Navigate the Internet to gather information)

**The importance of employability skills**—In 1990, the U.S. Secretary of Labor appointed a commission to identify the skills our young people need for success in the world of work. The purpose of the commission (which came to be known as SCANS, the acronym for Secretary’s Commission on Achieving Necessary Skills) was to support the development of a high-skill workforce for a high-performance, high-wage economy. Although the SCANS report (1992) is now over a decade old, its findings and recommendations continue to be a valuable source of information for individuals and organizations involved in education and workforce development, including development of the nation’s photonics workforce.
While the information presented in NPSST pertains primarily to the technical side of the commission’s findings, many members of the photonics business and industry community have noted that employability skills are no less important than technical skills (and are generally lacking in the current workforce). Therefore, in NPSST the skills listed for the six photonics areas include both technical and employability skills.

5.5 Knowledge Components

In preparation for the compilation of NPSST, educators from two-year colleges provided information that assisted the authors of NPSST in compiling a list of foundational knowledge components based on the tasks and skills requested by employers. Knowledge components are intellectual functions that, in specific combinations, form the basis for understanding concepts in science, engineering, and technology. With respect to NPSST, it can be said that certain knowledge components are essential for behaviors that enable photonics technicians to perform tasks using skills to accomplish critical work functions. For example, an understanding of Snell’s law of refraction enables a technician to match a particular light source to a particular fiber. The matching process is a skill, while the underlying principle (Snell’s law) is a knowledge component. A good understanding of knowledge components enables technicians to apply principles and techniques to the design, fabrication, modification, and operation of optoelectronic devices and systems.

Some of the knowledge components listed in NPSST will have been learned before students enter two-year postsecondary programs while many will be learned while students are in the programs. In either case, some knowledge components represent core principles that are invariant; that is, they do not change even though the technology and applications based on them do. On the other hand, some knowledge components deal with the operation of a particular optical device such as a Q-switch or a tool such as an optical power meter. In these cases, the knowledge is variant, since its relevance depends on the current state of technology, even though using the device or tool may also require knowledge of invariant laws, principles, or theories.

Comprehending the interplay between invariant knowledge (of laws, principles, and theories) and variant knowledge (of how to use the latest tools and devices) is one of the great challenges facing photonics students—and developers of skill standards such as those contained in NPSST. Yet educational institutions must strive to find the balance between the two if their students are to succeed both in the short and long term, that is, as soon as they exit their programs and throughout their careers as photonics technicians.

6. Curriculum Resources in NPSST

6.1 Overview

The curriculum materials provided in NPSST reflect a broad view of the educational process, as opposed to focusing exclusively on the two years required for associate degrees. Those two years are critical; for many photonics technicians, they mark the completion of formal education and the period of greatest concentration on the tools of the trade. But they are not likely to produce optimum results unless they are logically coordinated with the four years of high school that precede them.

For this reason, the curriculum recommendations offered in NPSST follow the 4+2 Tech Prep model. That model, which is supported by most community colleges across the nation, lays out career pathways that enable students to build a strong academic foundation while acquiring technical and employability skills relevant to the career clusters of their choice. The technical focus of the model is general at first and becomes increasingly specific as the student progresses from each grade to the next. The model not only gives high school students a sense of direction but provides the background in mathematics and science that will allow them to attain higher skill and knowledge levels during the first two years of postsecondary education and to pursue further education, if they so choose.

The courses specified in the 4+2 course sequence provided in Figure 1 are based on the employability and technical skills and on the foundational knowledge components listed in NPSST. The 4+2 course sequence provides a model educational pathway for students to follow in beginning their photonics studies in high school and, upon graduation, transitioning smoothly to cooperating community or technical colleges.
The courses specified in the figure indicate the technical content, scope, and sequence recommended for a broadly-educated photonics technician. (NPSST provides outlines for three high school courses—Career Management Success, Computer/Software Applications, and Introduction to Photonics.) The twelfth-grade course Digital Electronics (*) could be offered for dual (secondary-postsecondary) credit. The technical elective (**) could be either of the first two college photonics courses, Fundamentals of Light and Lasers or Optics and Optical Components (for which NPSST also provides outlines). The two technical courses marked “Photonics Specialty” provide for specialization in one of the six photonics specialties around which the standards in NPSST have been grouped.

The figure shows how the 4+2 course sequences divide programs into three two-year layers that systematically increase the student’s concentration on his or her career specialty. In the first layer (“foundation,” grades 9 and 10) students study “contextual” academics (math, science, language arts, other), begin career exploration, learn employability skills, and learn to apply technology skills to their fields of interest. In the second layer (“technical core,” grades 11 and 12) students study increasingly advanced contextual academics, acquire knowledge and skills for the technical core of the fields they plan to pursue, and participate in work-based learning experiences such as job shadowing and summer internships. Twelfth graders usually take at least one dual-credit postsecondary course. In the third layer (“technical specialty,” postsecondary years 1 and 2) students focus on their career areas in-depth but are encouraged to continue work in academic fields and the humanities. Students who complete this layer are qualified for employment in their areas of specialization or, if they so choose, admission to baccalaureate degree programs.

6.2 STEP II Courses (Postsecondary)

NPSST provides outlines for the following eight postsecondary courses.

1. Fundamentals of Light and Lasers
2. Elements of Photonics
3. Optics and Optical Components
4. Lasers and Other Light Sources  
5. Detection and Measurement  
6. Fiber Optics and Communication  
7. Imaging and Display  
8. Photonics Applications  

The outlines are laid out in sequenced modules that identify the information that should be covered in each course and suggest an order of presentation that will enable students to synthesize new information by building on information covered in previous modules.  

The outlines reflect an attempt through the combined efforts of two-year postsecondary educators, industry representatives, and the authors to achieve an optimum balance between variant and invariant knowledge. The outlines are modular, which means, among other things, that some material is presented more than once, though each time from a different perspective. This is to be expected in a situation in which the acquisition of variant knowledge depends on having already acquired certain invariant knowledge.  

7. Future Plans  
The larger picture for STEP involves the completion of STEP II and a final three-year phase for further curriculum development and implementation called STEP III. In STEP II, the project will complete a thorough revision of instructional modules developed under STEP I. The revised modules will be piloted beginning in fall 2003. The next two challenges for the project are creation of additional modules and preparation of teachers to teach the modules.  

NPSST calls for 54 instructional modules. Under STEP II, the NSF has provided funding for development of seven modules beyond the eleven that already exist. The goal of the project’s principal investigators is to identify business and industry sponsors for another seven modules. The hope is that for each of those seven modules, an industry sponsor would provide (1) the $25,000 necessary for development, (2) examples of equipment or materials that may be used for instructional purposes in the module, and (3) technical assistance for the author as needed.  

Faculty preparation for STEP II is to be handled using a three-pronged approach. First, online courses will be used to assist faculty who have technical backgrounds but no expertise in optics or photonics technology. The intent is to develop single courses in introductory optics/photonics at schools that have never offered the topic before; the courses would be offered as electives for other technology programs. Second, the project will provide two half-day short courses that introduce experienced faculty to the curriculum. Finally, the project will support a capstone symposium with faculty who have used the curriculum material during the pilot program to allow them to discuss with their peers their experiences in using the STEP curriculum.  

8. Conclusion  
Development of NPSST is the first critical task of the STEP II project. The goals of the STEP II project continue to build on that critical first step, as well as the foundation laid by the STEP I project. Those goals are (1) development of up-to-date photonics curriculum materials; (2) promotion, dissemination, and facilitation of the use of project materials at community and technical colleges; and (3) demonstration of how articulated curricula, beginning in the ninth grade and continuing through the baccalaureate degree, enhance the value of associate degrees in photonics by making the transition from high school to two-year colleges seamless and by providing options for education beyond the associate degree. Achievement of these goals will require further assistance from business and industry in the development of additional curriculum, and support for STEP III in the coming years.  

NPSST is available, without charge, to any organization, employer, and/or educational institution. Local partnerships or employers and educators are encouraged to study the document and use it as a guide for improving, updating, and initiating photonics programs at two-year colleges in their areas. CORD staff members are available to provide assistance if needed.
Diagnostics

In a situation where curricula did not adjust at the required pace and many students are getting attracted out of science and technology, the shortage of skilled workers at the technician and engineer level is known to be a threat to development. In spite of a serious crisis in 2001, the trend of an increased presence of optical technologies remains unchanged and is bound to remain part of the landscape for decades. The level of investment required and the markets make Europe the best scale to plan for unified curricula and a global analysis of the human resources needs. There is no agreement on the definition of a trained optician, and European countries differ in the way they educate opticians, source of a lack of clarity and visibility which is detrimental to attracting good students and to the job market. Through its closely work with companies, OPTRANET will propose measures to enhance the adequacy and the visibility of the training offer.

The field of Optics and Photonics has evolved in the past 15 years into a professional domain with a need for highly skilled people and a growing importance of specific technologies. Specialised curricula at various levels of teaching, journals, learned societies and industrial activity clearly show that Optics/Photonics is a fairly well defined field with a significant growth rate.

For cultural and historical reasons, in particular related to language issues, European countries have developed independent systems for education in the field of OP as in many other fields, in relation between their higher education system and their industrial needs. Mutual knowledge and recognition between countries has been a marginal issue so far. At present, there is no agreement on the definition of what could be called a trained engineer, and European countries differ in the way they educate opticians: France has specific degrees, while Germany is developing specialized curricula and most other countries include optics as part of electrical engineering, physics, applied physics or optoelectronics. This creates a lack of clarity and visibility which is detrimental to attracting good students and to comply with the job market.

Because the situation we face is a period of such a fast evolution, it is hard to judge what jobs might be in demand 5 or 10 years ahead. Skills sets must be constantly upgraded to keep up with the fast pace of global markets. One of the reasons for focusing our program in strengthening the relationships between industries, research laboratories, universities and secondary schools is that it seems to be the best way to produce experts in technology transfer (the lack of skilled people in technology transfer has resulted in some weak industrial positions of Europe compared to the US or Japan, for a similar quality of research).

**Contribution to Training policies**

As mentioned in the European report on education and training in employment policies, “One of the challenges facing education and training systems is to ensure that the supply of education/training meets demand from both individuals and businesses.”

As Optoelectronics is a quite new and worldwide industry with international competition for materials, technology and people, national answers for the above challenges are not significant. The level of investment required and the markets make Europe the most appropriate area to plan for more unified curricula and a global analysis of the human resources needs...

Besides that, training policies ask for new schemes to adapt the content of education / training programme, and the whole European policy or initial training is only on a phase of definition.

By exchanging experience with the actors who implement such policies and procedures to develop a better matching between industrial reality and academic training, we can propose concrete actions towards schools and
colleges that strongly attract pupils to science and that will permit teachers a better understanding of the skills to develop.

**Contribution to Industrial policy**

“The industrial policy of the Community aims at creating a knowledge-based society with enterprises operating on markets open to international competition. This policy is intended to foster innovation, sustainable development and the removal of obstacles to change. In addition, it seeks to promote Europe as a location for investment by companies, whatever their origin, and to enhance the competitiveness of European industry in an increasingly globalise context.”

Our proposal will fulfill the two main aspects clearly mentioned above.

By an increase of high skilled people, we will remove some obstacles to innovation. Our action concerted with the IST current project will allow us to work with up-to-date information.

It will be easier for foreign companies in optics/photonics to find adequate Human resources in Europe. This will help for promotion of Europe on the worldwide level.

**European added value of the consortium**

Optranet project will reinforce the European community in optics-photonics and the exchange of experience and practices between the different members.

**The contents of the optranet project**

The two-year Optranet project is part of the European IST (Information Society Technologies) programme and involves five partners: Great Britain (Oxford Innovation), Germany (Optonet, JENA region), Sweden (ACREO, Stockholm region), Poland (Warsaw University) and France (Opticsvalley, Paris region). Opticsvalley is the project's European coordinator.

It began in April 2002 and will be closed in April 04.

As showed below, the main industrial actors as well as the most dynamic companies are in the close environment of these partners:

**Opticsvalley** (near Paris): Alcatel R&D centre, Avanex (Nozay), Thales LCR (Orsay), Thalès optoelectronic R&D centre (Guyancourt), SAGEM, Motorola R&D centre (US),


**Oxford region**: Agilent technologies, JDS Uniphase (US), Marconi, Nortel Networks (US), booklam.

The European added value of the consortium is in their complementary skills and in the networks they manage.

These actors are well established in their own countries. They keep close contact with SMEs and large companies in their environment, which will ease the collection of relevant information about training needs.

The project’s mission statement could be summarised as **Highlighting and promoting the European training Offer in Optics and Photonics.**

The general program can be divided in 4 parts:

1/ Bridging the gap between industries, education and training in their environment

This section is a first trial to structure the different initiatives supporting optics and photonics in Europe. Different initiatives have already structured the European landscape in this field.

In Germany, the Bundes Ministerium für Bildund und Forschung (BMBF) promoted a network of 7 regions.

In France, a network of 7 “poles” covering the most dynamic sectors (St Etienne, Marseille, Lannion, Bordeaux, Paris, Grenoble) has been built these last 2 years.
In the United Kingdom, a network brings together Scotland (represented by Scottish optoelectronics Association), Wales (Welsh optoelectronics forum), South-East England (SEPNET: a structure with excellence centres from Southampton, Oxford ...)

2/ Identifying new training needs by polling companies, research centres and corporate training centre

With the support of the network created to carry out the poll, OPTRANET will deliver the main elements available for the development of an Optics and photonics observatory dedicated to training needs for the next decade.

The objective is to carry out a survey of companies to find out how training matches the career opportunities in each country. The study will make recommendations to structure the optical syllabus.

OPTRANET will help define the required skills for a graduate at the technician or engineer level for a better adequacy with the industrial needs, and will validate it at the European level. This should increase professional mobility (for example, a national degree will be accepted or validated in any other European country) as well as student mobility (this European curriculum will enable students to continue their studies after moving in another country).

At the end of this project, OPTRANET will have delivered a complete overview of the European training offer in optics photonics and linked industries, as well as identified the needs of competencies required by the industry. This resource will be the cornerstone to elaborate basic European curricula for initial and continuous training. All these information will be delivered through the OPTRANET website that aims to become the European website for Training in Optics and Photonics. Standardisation in training is another key element of our action. Through the use of European Credit Transfer System, we will enable higher education institutions to adapt these core European curricula into their own current and future courses.

Our objective is to drastically increase the number of higher education institutions involved in optics and photonics using ECTS system.

3/ Highlighting careers and challenges, to make people aware of these technologies. To increase the flow of future engineers and highly skilled manpower, OPTRANET will develop the interest of pupils and young people mainly in secondary schools using hands-on experience and mobile exhibitions. Our “awareness’ objectives” include the experimentation of optics toolkits with hundreds pupils, and the participation to 5 National major events (comparable “La fête de la science” in France).

4/ Promoting the ECTS (European Credit Transfer System) which measures and compares the courses taken by students and ensures that there are sufficient points of similarity between the establishments using it, so that the various countries of the European Community can cooperate.

Our plan should drastically increase the number of establishments that use it.

To help students make the most out their study abroad and facilitate student mobility within Europe, the European Commission has developed a European Credit Transfer System (ECTS), which provides a way of measuring and comparing learning achievements, and transferring them from one institution to another. ECTS has been adopted by a variety of countries in Europe and is a method of standardising course content from Universities within Europe.

The European Commission promotes studies abroad as a means of improving the quality of academic cooperation and, therefore, bringing benefits to students and higher educational institutions. Studying abroad is perceived to be a particularly valuable experience for young people. It is a good way to learn about other countries, ideas, languages and cultures.

Students who plan to study abroad typically look for:
Study programmes which are relevant for their final degree
Full academic recognition that ensures that they will not waste time in completing their degree by studying abroad.
It is a credit accumulation system that has developed rapidly throughout Europe. In the countries within Europe, students normally are granted 60 credits for a year (and 120 credits in the UK). The number of ECTS credits is determined by the student workload. This includes lectures, laboratory work, private study, library time, coursework, continuous assessment and examinations.

At the moment a great deal of training centres do not use the system and European students are not well informed about it.

The Optranet pedagogical kit

An Optranet teaching kit has been manufactured in France by a French company which markets training materials (DMS/ DIDALAB). Four copies of the kit have been released (three for France and one for Great Britain).

They are used in France: through the network of physics teachers, in the French optics clusters through the contacts those clusters maintain in the field of education at exhibitions, colleges and school open days and any fairs promoting scientific and technical education.

The teachers who use the teaching kit rely on quality equipment to explain the main aspects such as the components of light, the formation of an image and the propagation of light. Young people will thus learn what a laser or optical fibre is and how they are used in everyday life. They can go further and learn about polarization. They can also understand the role of the glass and optical components used to manufacture instruments that use light.

Brochures are available to set up the equipment and conduct the experiments. The history of the optical field is introduced as well as applications fields. Slides can help teachers explain optical phenomena.

For the French version of the optranet kits, we have filmed a documentary called “Demain un métier dans l’optique” (6 minutes): “Tomorrow a job in optics” which explains the sector and the different technologies. We have underscored the training curricula and courses linked the engineering, technician and operator jobs. This film is distributed through opticsvalley and its network of the French optics clusters.

The “Spectrum Mobile” is a travelling exhibition in a small truck that visits colleges and high schools in England and in the European countries as France and Germany thanks to the optranet project.

It’s an interactive way of demonstrating light and how it is used in everyday life: a demonstration of light and electricity following the electromagnetic spectrum in a 5.5m mobile unit. It connects education and the national curriculum with the Optoelectronics industry in a stimulating and relevant manner by:

- Introducing the concepts of Optoelectronics
- Demonstrating the use of photonics in our everyday lives by enabling pupils to find out how photonics based communication systems work.
- Modular interactive circuits are set up to explain principles and operation
- Curriculum delivery units guide participants through displays and practical activities.
- The Challenge section offers a variety of activities from building solar powered vehicles to controlling robots using programmable chips and infra-red communication

Website: www.formulaschools.com/electronics/spectrum.htm

The Cobrabid and Sensomed polish kits are also used in Poland to promote the optical field

The European website

Its address is www.optra.net

It was started in April 03.

The site’s targets are:
- Students who want to study optics in other countries.
- Students who want to broaden their knowledge of the field.
- Teachers in the optics field
The site aims at publicising the work done by the partners on the following subjects:

teaching and pedagogical kits
courses available and descriptions of the qualifications and degrees with an indication of how they match up in a table form
surveys of the companies and a summary of the conclusions with recommendations for any new courses
ECTS and its promotion to campuses that do not use it
information in the form of news items on teaching optics and photonics: a new qualification, an exhibition, a conference
4 newsletter to be produced by the partners

The major components of the site are:
Training and ECTS
Pedagogical kits
Surveys

Training part:

Keeping in mind the fact that the difficulty in Europe lies in the absence of equivalent degrees, diplomas and qualifications commonly shared by all countries, we have detected qualifications which have been defined at four levels:
vocational training
advanced vocational training
Undergraduate
Graduate and postgraduate

These qualifications are mandatory to open up "job opportunities" as:
operators,
operators/technicians,
superior technicians,
Engineers.

Practically it’s possible to find other qualifications in the different countries by using a search engine.

We currently have included:

174 diplomas and degrees:
61 in France
94 in Germany
5 in Poland
3 in Sweden
11 in UK

293 training centres:
212 in France
43 in Germany
19 in Poland
9 in Sweden
10 in UK

Survey part:

All the project partners carried out a survey of companies to find out how training matches the career opportunities in their own country by sending out a questionnaire.

We sent 630 questionnaires or conducted face to face interviews. We received 185 answers.
We contacted more than 30 training centres in the optical field.
The results are on line.
Each country made recommendations to explore and implement.
The ECTS (European Credit Transfert System)

For the optranet website we have defined two targets:
the students
the training centres

For the students, the training centres that use already the system are listed. We are putting the list on line to keep informed the students about the possibilities of exchange.

For the second target (the training centres), we deliver on the website, information on the system, with documents which explain:
how to implement the system
who the ECTS representatives are
what forms should be filled
what is implied in terms of work and preparation

Some experiences will be described on the website.

Three meeting have to be organized to introduce the Methodology to the training centres, until completion of the project in France, United Kingdom and Germany.

WORKSHOPS AND COMMUNICATION

☞ We have organized a first workshop with a roundtable in Oxford on April 2003, around the theme: » The results of the surveys". Industry was present. There was a general consensus that there was not enough emphasis placed on optics at the undergraduate level for technicians (for example).

☞ The second workshop will be held in Jena in Germany on November 2003. The theme will be: “Laser and technology: toward a vivid European cooperation in academic training”
Each project partner will attend with a training specialist centres from their country, to promote contacts between teachers and the campuses in Europe.

☞ Communication about the training courses in the bio-photonics field is planned at the time of the OPTO trade fair in Paris on October 2003. An experts committee will be launched then.
It will suggest state of the art leads to implement contents and training courses at the technician and engineer levels in the bio-photonics field.

☞ 5 national events for the dissemination of the optranet kits in France, England, and Poland are scheduled this year.
For example, the “Fête de la Science" in France, organized each year in October, is a major event where children and their family, pupils and their teachers can participate and visit the laboratories or science campuses to increase awareness on technical and scientific phenomena.

CONCLUSION

By exchanging experience with actors who implement training policies in order to better match the industry needs and the academic training, Optranet proposes concrete actions which:
strongly attract pupils to science
will permit teachers to reach a better understanding of the skills to develop
Will contribute to highlight the European competencies in optics.
The Ontario Photonics Education and Training Association (OPETA): l'Union fait la Force!

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Abstract: OPETA regroups all parties interested in the supply of highly-qualified photonics personnel in Ontario. The association counts more than 60 members from Ontario’s universities, community colleges, grade/mid/high schools, government agencies, private curriculum developers/providers and industry. In its third year, with a list-serv, webpage, regular meetings and coming off distributing to its members ~$3-million in donated equipment, OPETA is a key element in local networking, helping photonics education flourish in Ontario at all levels.

1. Introduction
Photonics is to be in the 21st century what electronics was in the 20th, and it is often called “the next multi-trillion-dollar industry”. But one could say that – more than an industry – photonics is a key enabling technology that cuts through all industry sectors, from medicine to manufacturing, from research to consumer products, from art to telecommunications. It is certainly a crucial strategic technology for Canada, and for Ontario in particular. So why are so few people educated and trained to work in photonics? And what can be done about it?

These two questions are the basis for the formation of OPETA, the Ontario Photonics Education and Training Association (www.opeta.ca). In Ontario, where technology giants like Nortel Networks and JDS Uniphase rub shoulders with a growing number of feisty small-and-medium photonics companies, the demand for highly-qualified personnel in photonics – at all levels – much outstrips the supply. One of the reasons for this problem is that most photonics experts are produced in Ontario universities’ graduate schools, with few ever touching a laser or optical fibres before that. This modus operandi yields too few workers in too narrow a slice of society to fill all the positions, which range from assemblers to technicians to engineers to researchers. As this pressure for more photonics-knowable workers grew through the end of the 1990s, several educational institutions and private trainers have put together courses, programs, workshops and seminars in photonics to respond as best as possible. It quickly became clear that many of these efforts had to face similar challenges – among which developing new curriculum, finding qualified instructors, petitioning companies and governments for support, and recruiting students – and that banding together would benefit everybody, including industry and the students. This paper presents a successful model for networking, as applied to the photonics education and training community in Ontario, Canada. It is hoped that it can be used as a blueprint for others to start similar associations worldwide, and to enable networking of photonics education and training experts on a global scale through the nascent Global Photonics Education Network (GPEN), which is the subject of another paper in these proceedings [1].

2. Out of chaos came (a semblance of) order…
At the end of the 1990s, there was such a strong demand in Ontario – and indeed, worldwide – for workers qualified in photonics that much pressure was applied by the industry on the education system to provide said workers. With the seemingly unending exponential growth of the telecommunications industry in particular, large companies like JDS Uniphase, Nortel Network, Alcatel, and GSI Lumonics were in dire need for personnel at all levels, from assemblers to technicians to scientists. This human resource crisis was only exasperated by an increasing number of start-up companies with staggering growth, most of which were well funded by the venture capital community. These start-ups were in desperate need of R & D scientists to bring their new products to market and establish themselves before their next round of financing. Add to this the increasing use of photonics in other industries like automotive, biomedical, manufacturing, etc., and one was faced in the province with a bottleneck to the growth of the sector resting on the availability of highly-trained photonics personnel. At one point, more than 40% of the Toronto Stock Exchange’s TSE 400 index was dominated by telecom-related stocks [2], so this was no light matter and it needed to be addressed quickly.
2.1 A bevy of new programs in photonics education and training

It was in this fertile ground that several new education and training programs in photonics independently started in 1999-2001, before the full telecom downturn had a chance to take hold. Addressing the need for technicians and technologists, Photonics Research Ontario (PRO, Toronto), Niagara College (Welland) and Algonquin College (Ottawa) established together 2- and 3-year programs at the colleges in a 4-year, $7.6-million curriculum-development and implementation project mostly funded by industry and the government of Ontario. Vitesse (Re-Skilling) Canada (Ottawa), the Canadian Microelectronics Corporation (CMC, Kingston), the University of Toronto’s Professional Development Centre (PDC, Toronto), the University of Waterloo’s epSTAR (Waterloo) and Algonquin College were starting continuing education programs to provide photonics top-ups for scientists and engineers already possessing degrees to facilitate their slide into this sector with huge personnel demands. McMaster University (Hamilton), Carleton University (Ottawa) and Wilfrid Laurier University (Waterloo) were putting together full-blown undergraduate degrees and specializations in photonics through their Engineering, Physics and Physics/Computer departments, respectively, to address the need for engineers and scientists.

All the while, graduate schools at most large Ontario universities (Toronto, McMaster, Waterloo, Ottawa, Carleton, Western Ontario, Queen’s) were increasing their research programs in photonics. This was in great part enabled through recent additional funding opportunities in Canada and Ontario stemming from the improved financial situation of the country. On the first year in decades that Canada posted a budgetary surplus (in 1997), $800-million of it – a significant portion – was earmarked for the creation of the Canada Foundation for Innovation (CFI) to help with research infrastructure. Provincial matching funding agencies were started in many provinces to facilitate the access to CFI for its university professors. Many new photonics-related research programs were started or enhanced through this new source of funding, and through a better funded Natural Sciences and Engineering Research Council (NSERC).

2.2 More confusion than solution?

All this effervescent activity featuring several new players in photonics made for a rather confusing state of affairs from industry’s and the student’s points of view: What are all these programs? Which one is best for my needs? What are the differences between them? Adding to this was the general feeling of suspicion with which several of these educational institutions eyed each other: What are these other programs? Are they going to target the same student pool as ours? How are we in competition? Because of Photonics Research Ontario’s privileged position as the Ontario Centre of Excellence mandate to support the growth of photonics in the province, it was involved – in one way or another – with most of these new education and training programs. In order to clear the air and focus the various stakeholders on the main task at hand – providing high-quality photonics workers to industry – a “summit” of all known non-graduate programs providers was called by the author, who is the Manager of Photonics Education and Training at PRO, for 6 June 2001. At this “summit”, participants from universities, colleges and independent curriculum providers exchanged information about their respective programs and networked extensively. It was quickly realized that each had much more in common than was thought, including the challenges ahead of teachers and students recruitment, and access to resources and funds. A main point emphasized at the “summit” was the almost non-existent voice the photonics education and training community had in the spheres of politics and the general public. In light of all this and the success of the “summit”, all participants agreed to form an association to pursue together the common goal of providing photonics education and training in Ontario. Thus was born the Ontario Photonics Education and Training Association, or OPETA.

3. OPETA: a photonics education and training “cluster”

In the beginning, OPETA was little more than 14 people from 9 institutions, held together by a desire to establish good, solid programs in photonics. Even as such, OPETA was the start of a photonics education “cluster”. A cluster is a group of local companies, educational institutions and other stakeholders rallying around a particular sector of the economy or industry [3]. By pooling resources, a cluster can network, share best practices, influence local politics, and lobby provincial, state or federal levels of government. One of the essential aspects of a cluster is that it be local, regrouping members from within, say, a 50-100-km radius (in OPETA’s case, this is expanded to the whole of the province of Ontario). In photonics, the industry clustering efforts worldwide have been led by Dr. Bob Breault from Breault Research Organization in Arizona (USA). There exists now photonics industry clusters throughout the world [4]. Example of photonics education clusters include the National Association for Photonics Education and Training (NAPET) in Singapore and Project PHOTON in New England (USA). One of the main
The tenets of clustering is that even competitors are better served working together for the growth of the whole of their sector, to increase the pie – so to speak – instead of solely trying to get a bigger piece of a constant-size pie.

Because networking is a key component of a cluster’s activities, much effort was spent in the early days of OPETA to establish efficient and successful means of communications, both internal and external. These are centered around a three-pronged approach including regular face-to-face meetings, a list-serv, and a webpage.

3.1 Regular OPETA meetings and Mission/Vision statements

The most important regular events staged by OPETA are its meetings. These were held for the OPETA members to network face-to-face every 3-4 months, rotating throughout the province. Thus far, meetings were held in Waterloo (inaugural “summit”), Hamilton, Niagara, Ottawa (first Annual Meeting), Toronto, Hamilton, London (second Annual Meeting). Much gets accomplished in these meetings, including setting the priorities for the year, striking committees to address particular issues or events and keeping each other informed of recent progress in our programs.

One of the first things on OPETA’s plate was to establish what its priorities and goals were, in essence what its Vision and Mission were. Through the first two meetings, the following Vision and Mission statements were hammered together:

**Vision:** To foster, through its members, the provision of world-class education and training for all photonics needs in Ontario.

**OPETA intends to achieve its vision through five Mission Statements:**
1. Coordinating and leveraging Photonics Education and Training (PET) efforts;
2. Facilitation exchange and collaboration between educators;
3. Promoting PET to industry and government;
4. Outreaching to schools and the general public; and
5. Interacting with all stakeholders to assess and analyse the needs in photonics education.

Based on these Vision/Mission statements and the on-going projects, the draft agenda to each meeting is set by the Chair (the author, since OPETA’s inception), with input from the membership. After the usual bookkeeping items (welcome, review of the agenda, review of last meeting’s minutes), each member present gives a short (5-10 minutes) update of his/her activities, time is allowed for networking, and particular issues are tackled (Annual Meeting, organization, webpage update, equipment donations, etc). Meetings are usually scheduled as half-day events, with lunch and coffee breaks provided by the host institution or OPETA’s budget.

3.2 The OPETA list-serv and webpage

The second means of direct communications established in the week following OPETA’s inaugural meeting was the list-serv. A list-serv is a single email address to which a member from the list sends an email that will reach all the other members of the list. It is the simplest way to reach everybody at the same time. When meetings have to be set, policy has to be discussed, new resources have to be publicized, it is a very useful tool. There is usually a list-serv manager who screens new applicants for relevance, but individual postings on the list are not routinely screened, they go directly to the list members. A general etiquette has to be followed when using list-servs to avoid mass mailing intended to only one member, or to avoid spam. There are several commercial but free list-serv providers where all the exchanges are archived and can be accessed only by the members of the list; OPETA uses Topica.com and has had great success with it. The most glaring limitation encountered with Topica is a 100-kilobyte message maximum, which greatly reduces the possibility of sending attachments. Nonetheless, in its 2+ year of existence, the OPETA list-serv has conveyed more than 300 messages between members, making it OPETA’s most important link between members.

In order to have a web presence for the outside world, OPETA established its webpage at [www.opeta.ca](http://www.opeta.ca). The webpage serves as a resource centre for the members, with documents, links, forms and other information posted for their viewing. The webpage also serves as a recruiting tool. It is currently in the process of being revamped.
4. The importance of coming together

Of course, the explosion of photonics education and training programs that led to the formation of OPETA mostly took place before the current – and soon ending? – telecom slow-down. Some of these programs were mothballed or considerably altered in view of the change in demand from that dominating sector of the Ontario economy. The main issues that motivated the start of OPETA:

- How can we work together to answer this immediate mammoth human resource need?
- How can we secure an affordable supply of instructors when they are all being hired by industry?
- How will we be able to pay for the costly equipment needed to teach this technology?

were soon replaced by others:

- How do we adjust our curriculum to answer the demand from different sectors (manufacturing, biomedical, lighting, automotive)?
- How do we find our graduates good jobs?
- How do we ensure the long-term viability of our programs for such a time as when the demand increases again?
- How can we best leverage the industry’s woes into something constructive for us and the sector in general?

Again, the power of association was evident in this critically different climate. As of August 2003, OPETA counts 66 members from 46 organizations (academic, governmental and industrial, see Table 1 for the list). In the sections below are some examples of accomplishments by OPETA as a whole and individual members.

Table 1. OPETA member organizations, as of August 2003, showing the diversity in geographical representation (all of Ontario, some in Nova Scotia and one in Scotland), educational levels (Outreach, Grade/Mid/High Schools, Colleges, Universities, Continuing Educations) and sectors (educational, governmental, industrial).

<table>
<thead>
<tr>
<th>Colleges</th>
<th>Government/Clusters</th>
<th>Continuing Education Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algonquin College (Ottawa, Ontario)</td>
<td>Canadian Microelectronics Corporation (CMC)</td>
<td>epSTAR</td>
</tr>
<tr>
<td>Canadian College of Business and Computers (Toronto, Ontario)</td>
<td>Centre for Microelectronics Assembly and Packaging (CMAP)</td>
<td>Lightguide Systems</td>
</tr>
<tr>
<td>Durham College (Oshawa, Ontario)</td>
<td>Canadian Photonics Consortium</td>
<td>Physiciens Sans Frontières</td>
</tr>
<tr>
<td>George Brown College (Toronto, Ontario)</td>
<td>Department of Foreign Affairs and International Trade (DFAIT)</td>
<td>Valkom</td>
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<tr>
<td>Niagara College (Welland, Ontario)</td>
<td>Strategic Microelectronics Consortium (SMC)</td>
<td>Vitesse (Re-Skilling) Canada</td>
</tr>
<tr>
<td>Universities</td>
<td></td>
<td>S &amp; T Outreach Organizations</td>
</tr>
<tr>
<td>Acadia University (Wolfville, Nova Scotia)</td>
<td>National Capital Institute for Telecommunications (NCIT)</td>
<td>Let’s Talk Science</td>
</tr>
<tr>
<td>Carleton University (Ottawa, Ontario)</td>
<td>Ottawa Centre for Research and Innovation (OCRI)</td>
<td>Scientists in School</td>
</tr>
<tr>
<td>Dalhousie University (Halifax, Nova Scotia)</td>
<td>Ottawa Photonics Cluster (OPC)</td>
<td>Science and Technology Awareness Network (STAN)</td>
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<tr>
<td>McMaster University (Hamilton, Ontario)</td>
<td>Ontario Photonics Technology Industry Cluster (OPTIC)</td>
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<tr>
<td>Strathclyde University (Glasgow, Scotland)</td>
<td>Photonics Research Ontario (PRO)</td>
<td></td>
</tr>
<tr>
<td>University of Guelph (Guelph, Ontario)</td>
<td>Ontario Research and Development Challenge Fund (ORDCF)</td>
<td>The City School (Toronto, Ontario)</td>
</tr>
<tr>
<td>University of Ottawa (Ottawa, Ontario)</td>
<td>Ontario Institute for Studies in Education (OISE)</td>
<td>Dennis Morris High School (St Catharines, Ontario)</td>
</tr>
<tr>
<td>University of the Ontario Institute of Technology (Oshawa, Ontario)</td>
<td></td>
<td>John Paul II Catholic Secondary School (Scarborough, Ontario)</td>
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<td>University of Toronto (Toronto, Ontario)</td>
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<tr>
<td>University of Waterloo (Waterloo, Ontario)</td>
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<td>Wilfrid Laurier University (Waterloo, Ontario)</td>
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<td>Companies</td>
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<td>Wilfrid Laurier University (Waterloo, Ontario)</td>
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4.1 Toward an integrated photonics education and training continuum

Three years ago, in 2000, there were no undergraduate programs in Ontario exposing students to optics, lasers and photonics more in-depth than the usual “Optics and Waves” or “Electromagnetic Theory” courses in the Physics, Chemistry and Engineering departments. There certainly were no complete programs targeting photonics. With its first foray into the community college system, Photonics Research Ontario drew up a plan to establish a continuum of photonics education, “from grade school to grad school” as it became known. Figure 1 shows the pyramid on which this continuum is based. Traditionally, students were not being exposed to lasers until entering graduate school in Physics, Chemistry or Engineering. Not only is this too late in the education pyramid, but this modus operandi only offer Master’s and PhDs as photonics experts, failing to address the other levels. A comprehensive solution to the demand for photonics experts starts with more grade-school and high-school students being exposed to optics; with more parents and high-school career counselors knowing about photonics and recommending it as a career. Hence, a strong community awareness effort is needed, through print, radio and TV media. Full photonics programs have to be implemented at all post-secondary levels, in community colleges and at universities. For those already in the workforce needing a top-up in photonics, continuing education or crash courses in photonics (such as laser safety courses) need to be available.

In order to know where photonics education leads, what is also needed are clear career paths resulting from Photonics Technician and Technologists diplomas from community colleges, Bachelors of Science and Engineering in Optics from universities, or re-training opportunities for already-employed high-tech workers. While some of these types of programs are found in a few areas in North America, access to a comprehensive suite of programs in photonics is still limited (Rochester, NY, is a rare example, with Monroe Community College, the Rochester Institute of Technology and the University of Rochester all offering programs in photonics/optics; the Québec City region is also blessed by programs at the cégeps de la Pocatière, de Limoilou and at Université Laval). Figure 2 shows the various education paths desirable to have in photonics. A student coming from high school should have the choice of getting a photonics education through the university or the college paths. A worker wanting to learn about photonics should have the choice of a professional education program or one customized for specific needs. A new graduate or third-year undergraduate university student in a non-photonics degree should be able to take a crash course in the summer (after graduation or before his/her last year).

This kind of integrated approach to education in any particular sector requires the buy-in from all the levels of education. This is why a cluster like OPETA is critical to this endeavor. By coming together and working toward the same goal, OPETA members have now covered the whole of this pyramid, as shown in Table 2. In particular, the networking through OPETA has enabled important partnering between institutions and facilitated articulations between the new programs to allow for the movement of students graduating from one program into another. Most of the programs listed in Figure 2 did not exist before 2001. Most have been greatly enhanced by their association with OPETA through networking, letters of support during funding or program proposals, equipment donations, etc…

Of particular interest in Table 2 is the development of full-blown bachelor’s degrees in photonics. Two universities and two colleges are going to establish in 2003-2004 programs with the final credential of bachelor’s in photonics.

McMaster University’s new Photonics Engineering program will be offered by the Department of Engineering Physics, and will be the first Engineering program of its kind in Canada. Like the existing Engineering Physics program, it will provide students with a broad background in basic Engineering, Mathematics, Electronics, and Semiconductors. However, the new program will provide students an opportunity to pursue Photonics in greater depth and to have that fact recognized in the program designation. Following McMaster’s successful pattern of five-year Engineering programs, a new B.Eng. in Photonics Engineering and Management and another in Photonics Engineering and Society will be introduced in parallel with the four-year program. The first students are expected to enter Level II in September 2003, with the first class graduating in the spring of 2006.

Wilfrid Laurier University’s Department of Physics and Computer Science is launching its new Honours B.Sc. Photonics with its first student intake in September 2003. The aim of the program is to develop a strong understanding of the theory and application of photonics, with specific emphasis on data communications and networks, and with practical hands-on exposure to optics, fibre optics, and lasers. Wilfrid Laurier University’s program benefits from the particularity that the department offering it combines both Physics and Computer Science, and that the thrust of the program would reflect this combination.
Fig. 1. The photonics education and training pyramid. Photonics should be taught at all levels, “from grade school to grad school”. Significant efforts also have to be deployed outside of the traditional school system to reach the general community and to provide continuing education on the subject. Only then can one provide photonics technicians, engineers and scientists: through the programs in place and through a constant “priming of the pump” at the base of the pyramid to continually get new recruit to enter the pipeline.

Fig. 2. It is also important to provide clear career paths and articulations between programs to increase the number of choices available to people interested in entering the photonics education and training stream. Good choices and flexibility throughout the education continuum are essential to augmenting the number and quality of highly-qualified photonics personnel in the workforce.
Table 2. New programs or enhancements of existing programs undertaken by OPETA members

<table>
<thead>
<tr>
<th>Programs</th>
<th>Year Started</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Professional Development</strong></td>
<td></td>
<td>U. Toronto’s PDC</td>
<td>Algonquin College</td>
<td>Vitesse (Re-Skilling)</td>
<td>CCBC</td>
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<td></td>
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<td>Canada</td>
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<td></td>
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<td>CMC</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Carleton U. (specialization)</td>
<td>(B.Appl.Tech.)</td>
<td>Niagara College (B.Appl.Tech.)</td>
</tr>
<tr>
<td><strong>Technologist and Technician</strong></td>
<td></td>
<td>Algonquin College</td>
<td>George Brown College</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Niagara College</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grade/Mid/High School Community Awareness</strong></td>
<td>Discovery Channel segments by PRO</td>
<td>Scientists in School (PRO-enhanced)</td>
<td>Let’s Talk Science (PRO-enhanced)</td>
<td>Science and Technology Awareness Network (STAN)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SLOME (PRO-enhanced)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRO Optics Kits Program</td>
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</table>

Niagara College and Algonquin College, already strong from their programs in Photonics Engineering Technician/Technologists, have been given permission by the Ontario Ministry of Training, Colleges and Universities to offer a 4-year Bachelor of Applied Technology (Photonics). The concept of 4-year degrees at the community-college level is a new one in Ontario, and competition was fierce in obtained the few allowed permissions. The college program is joint between the two institutions, with a common curriculum, shared library resources, student exchanges between the two colleges and co-op work-terms. Emphasis is placed on the applied aspect of the field, with the more hands-on experimental learning taking precedence in the first years and the more advanced theoretical subjects following in the latter years. This is a reversal from the usual sequence in a degree program, and the merits of this approach will be discussed. This program is in preparation for a first student intake in September 2004.

Another interesting development due in part to OPETA is the birth of the Science and Technology Awareness Network (STAN) in Ontario. This group, which effectively makes up a “science and technology outreach cluster”, is inspired by the success of OPETA and models itself after it. It regroups 56 members from the science and technology outreach community in Ontario. While not focusing on photonics per se, the work that its members do will increase the profile of science and technology with grade/mid/high school students as well as with the general public.

4.2 Facilitating equipment donations

The unfortunate – and temporary – downturn in the telecommunications sector in 2001 left several OPETA members scrambling to re-organize their programs to ensure that their students would be able to find good jobs upon graduation. Other programs were scaled down or put on the back burner. One of the silver lining of this otherwise
A deplorable situation was the sudden availability of millions of dollars in telecommunications equipment for educational institutions. As giant corporations were shedding inventory, some tried their best to be good corporate citizen and donated to colleges and universities. In one such example, JDS Uniphase, in Canada, distributed several million dollars in used and new equipment to 14 Canadian universities and colleges in 2001-2002. Coordinating such a complex donation – including 3rd-party valuation, packaging, delivery – required a considerable amount of JDS resources. Because of that, when a new wave of equipment was deemed available in Summer 2002, it would have been tempting for JDS to crush it instead of going through the effort of donating it…

Thankfully, astute OPETA members worked out a process by which JDS Uniphase would donate all this equipment to one source – OPETA – who would then take care of the valuation, handling, storing, and distribution to its members. By providing a one-stop recipient for JDS Uniphase, OPETA received in late Summer 2002 in excess of $3-million in equipment. Once the equipment had been moved out of the Ottawa JDS facilities and stored at Algonquin College and Carleton University, a 3rd-party valuation was undertaken, a call for proposal was launched and a competitive disbursement process was put in place to distribute the equipment fairly to all OPETA members interested. Eight proposals were received in Winter 2003, and an ad-hoc Donation Advisory Group was formed from OPETA members who did not submit proposals. By July 2003 – about one year after the beginning of the whole process – all the equipment had been distributed to the successful proponents. Among them were 5 universities, 2 community colleges, 1 private college and an outreach organization. This equipment is going a long way to enable several of the programs listed in Table 1. OPETA is currently in the process of securing another similar donation from another large photonics company.

4.3 OPETA as a spoke for the Global Photonics Education Network

There is a new networking effort being undertaken to link photonics educators from around the world, the Global Photonics Education Network (GPEN). Founded at the ETOP 2001 conference in Singapore, this group aims to facilitate the exchange of ideas, information and resources between educators globally to help with the implementation and delivery of photonics education and training programs locally. While the GPEN is still in its early days, it has been identified early that photonics education clusters such as OPETA, NAPET and Project PHOTON can act as ideal portals from the local to the global arenas. Already, members of all three of these clusters are part of the GPEN, and it is hoped that other such local education clusters can see the light of day elsewhere in the world. See the GEPN paper in these proceedings [1].

5. Conclusion

In this paper we present the Ontario Photonics Education and Training Association (OPETA) as a model for the local networking of educators in the specific field of photonics. OPETA started out of a necessity to organize a rapidly growing number of photonics education and training programs in Ontario. Going from 14 members representing 9 institutions to 66 members from 46 institutions in 2 years, OPETA has proven itself a valuable tool for networking, advocacy to industry and government, equipment donations and program coordination beyond the original expectations of the founding members. By including all levels of education, from grade school to grad school, as well as government agencies and photonics companies, OPETA strives to further its vision of fostering, through its members, the provision of world-class education and training for all photonics needs in Ontario.

Acknowledgements

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References

The article is devoted to the problems of internationalization of education in optics. The importance and specific character of internationalization for optical education including its main problems are analyzed. The ways of international integration on the university level are presented through the model of “step by step” solution of education comparability. The importance of international university networks in optics is showed.

Each country has its own “optical school”, with its traditions, history, strong scientific fields, famous teachers and researchers, etc. Internationalization of such national optical schools is one of important ways for improvement of the quality of university graduators in optics. Internationalization gives access to the best world experience, gives education closer connection with the world science and economics, directs toward international exchange of scientific knowledge and achievements. The following barriers can be mentioned on the way of internationalization:

- Difference between the university qualifying documents in different countries;
- Distinctions in the set of optical graduating specialties in universities in different countries;
- Different contents of educational programs and courses;
- Different status and role of department in a learning process;
- Lack of educational programs and courses in English language in not English speaking countries;
- Necessity of transition from a system of engineering training to a two-stage system “bachelor – master”;
- Foreign textbooks are not always accepted by national universities due to their orientation to another educational process;
- Absence of agreements between universities about mutual recognition of educational courses and programs;
- Absence of evaluating systems for the courses taught in foreign universities;
Distinctions between educational systems is an objective obstacle for internationalization of education. Russian national standards limit capabilities of comparability of education received at foreign universities. However internationalization in the field of optical education has a number of considerable advantages and features making this process much easier here than in other technical and, especially, humanitarian fields.

First, it is the high interest to optics and optical education in the countries keeping the high-standards in technical progress.

Secondly, it is uniqueness of optical education itself. Optics in itself is an elite science requiring severe fundamental physical and mathematical background and availability of unique laboratory facilities. As a result of such prerequisites the qualitative optical education can not appear in itself in any technical institute or university. It needs long time period of formation of its own “scientific schools” including scientific and pedagogical staff, traditions, building educational and scientific labs and departments with their strong fields of research and education. The elitism and uniqueness of optical education is generic for all countries. As an example we can see that even in technologically advanced countries there are only a few optical universities or optical faculties, whereas there are tens technical universities of a broad profile.

Therefore, in third, the universities of an optical profile are put in expedient conditions in comparison with other technical universities. All of them are well-known both in international scientific environment and one to another, thereby determining a narrow circle of the potential partners. The specialization of different optical universities is also a positive argument for internationalization of optical education, creating the reasons for academic mobility. Optical students wishing to receive additional knowledge in optical specializations, which they can not get in their home university, get opportunity to travel abroad and as a result to become broader professionals.

International university networks is one of the main form of cooperation today between universities from different countries. It is practically impossible to find foreign university, not integrated in international university networks. Universities work in close co-operation, supplementing one another on different directions of preparation of the specialists. Therefore it is extremely important to create inter-networks of optical universities, integrating potentials of Unites States, Europe, Russia and Asia, for development of productive international cooperation in the field of optical education.

Fourth, an important point is the similarity of the contents of optical education programs at different universities in the world. The differences basically exist in techniques of teaching and in quantity of hours in the programs for the practical, laboratory and lecture components. There are also essential differences in a system of testing of student knowledge. The similarity of a context of education programs in optics all over the world leads to considerable simplification of comprehension of universities, to minimization of activities on comparability of courses and mutual recognition of education programs that is a good base for international cooperation in the academic field.

In fifth, optics and optical education as a consequence has priority at a state level for many advanced countries as a “Science of the 21 Century”. This means that the level reached in the field of optics determines scientific and technological capabilities of the country.

The listed features demonstrate that internationalization in optical education has a number of
advantages and thus demands smaller efforts for its implementation. An optical specialization of universities and the distinctions in the structure of educational process boost the academic mobility. The opportunities to get knowledge and skills from different foreign “optical schools”, introduces exclusive interest for the students and teachers.

Internationalization of education is connected to its comparability and depends on the national doctrines of development of a higher education. National level is the case of the problems solution "from above". The approach "from below” – the university level is the most interesting to practice. Each optical high school is the subject of international relations. Universities have their contracts with the partners abroad, they receive international grants, train foreign students and post-graduate students, participate in international university networks. St.-Petersburg State Institute of Fine Mechanics and Optics (IFMO University) - the unique optical university in Russia, introduces its approach to solution of education comparability through development of short-courses modules in English language for the students from foreign universities. Short courses are the educational modules with the specific contents, which can be taught independently or supplement each other forming sub-programs and programs. The approach is based on the three-level model:

The first level - comparability of short modules/courses

The second level - comparability of the educational university courses

The third level - comparability of Education Programs (bachelor, master, specialist)

In brief this approach is based on the following steps made by the university on the way of internationalization of its education:

1) Negotiations with foreign universities about capability of certification of short educational modules (lectures, laboratory trainings, practical works), for example, according to European Credit Transfer System

2) Joint work of the teachers and international managers from IFMO and foreign universities on recognition of the short courses taught at IFMO in English as a constituent part of educational courses taught in foreign universities with giving the certain number of credits for each short course

3) Signing of the long-term interuniversity agreements about certification of short courses

4) Looking for financing for training students from foreign universities at IFMO University

5) Development of the long-distance short courses/modules for foreign students in English

6) Carrying out the training at IFMO University with its admission in foreign universities

7) Increase of amount of developed short courses/modules as parts of curriculum taught in foreign universities

8) Certification of the educational courses for foreign students at IFMO University on the basis of already certificated short-courses modules

9) Looking for financing for training of the students from foreign universities at IFMO University in the certificated educational courses
10) Development and certification of Education Programs taught at IFMO (degree - bachelor, master, specialist)

11) Development of the academic mobility: students and teachers

12) Discussion of the obtained experience and results at the level of national Ministries of Education

13) Dissemination of results among other optical universities.

It is necessary to mark, that internationalization of the university education is connected with internationalization of all levels inside the university, namely:

*First level* - university administration (rector, administration).

*Second level* - functional management and control (pro-rectors on areas of activity - educational, scientific, etc.)

*Third level* is a level of faculties/institutes (deans of faculties)

*Fourth level* - last, but extremely relevant – level of university departments.

For common success, internationalization as the mobility of people and ideas should work at all university levels.

The presented above approach includes only the most general problems arising on the way. Nevertheless, the presented approach is based on the quite real experience of the short-courses training of the students from European universities at IFMO University. The first university, which started to participate in this international program together with IFMO was Uppsala University, Sweden. Within five years the Swedish students take the two weeks laboratory training in different optical labs at IFMO University. Using the same module-type education scheme we successfully launched at IFMO University the Summer School Program in Laser Physics for Uppsala students. The Summer School Program lasts a one month and consists from a few independent short modules, which can be chosen by foreign teachers and their students in advance. Another way of successful international cooperation on-going at IFMO University is “sandwich” optical programs for PhD students. The regular questioning of foreign students and teachers participating in optical training in St-Petersburg State IFMO University demonstrates their exclusive interest to such international cooperation in the field of optical education.

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Abstract: The Young Spectroscopist Symposium is held annually for young scientists to present spectroscopic research projects. All ethnic groups are represented. Ratings are on merit alone without ethnic/gender considerations. The event is widely supported, with 80-85% attendance by previously disadvantaged population groups. Future developments are to extend support to young spectroscopists.

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OCIS codes: 300.6560Spectroscopy; 000.2060 Education

1. Background
Until 1997, the Young Spectroscopist Symposium (YSS) was held biennially at tertiary institutions in either Johannesburg or Pretoria. Academics who previously involved their students with the YSS were usually from a core group of South African Spectroscopic Society (SASS) members or colleagues in contact with these members. As a result of our national history, mainly the traditionally “white” scientific community supported the meetings, with the involvement of the traditionally “non-white” institutions being rare to non-existent.

In 1998, the newly elected Executive Committee took up the responsibility of being in charge of a very strong society with most of its founder members still actively contributing to the work it was doing. With successful predecessors such as emeritus professor James Willis, Dr Pat Butler, Dr Albert Strasheim and others, who had so much to give to the spectroscopic community in the past, it was essential that the society itself and the meaningful work it had done had to be continued. The society could not be allowed to slip into inactivity and a gradual loss of its members.

The Executive Committee aimed for the SASS to continue being of service to the new generation of spectroscopists, with enthusiasm in this science and the many fields of its application. The SASS had a proven track record for the advancement of knowledge and skill, which had to continue with new growth. Role models in the SASS were willing to support this ideal and help make it work.

The changes brought about as a result of our first democratic elections in 1994, meant that the SASS had to focus on bringing about change in the way we were operating. We were not naturally migrating fast enough across the racial boundaries that were a heritage from the past. Participation in our meetings and delegates attending our meetings were not a reflection of the country’s scientific population. Integration was taking place, but at a very slow rate. As a result of this, certain aims became the focus of the Executive Committee to achieve during their term of office. They were to:

- Include activities that brought the younger generation of scientist in the country to our meetings.
- Bring the younger generation of different cultural backgrounds together to start liaisons between those with common interests.
- Help as many students as possible who had grown up in rural and poor urban areas and probably had limited exposure to science and technological developments prior to their studies.
- Stimulate communication and interaction amongst the developing chemists/geologists/physicists and others in the membership.

Success in these goals would co-incidentally also lead to the added benefits of growth and the continuation of the society.

2. The current Young Spectroscopist Symposium “model”
2.1 Meetings representing all spectroscopists
In the light of the background above, the obvious place to begin working was in the existing forum for younger scientists, the YSS. Our country’s history made it difficult to arrange a scientific gathering with delegates of all our races attending and where the participants giving presentations were fully representative of our population.
It was decided that the best approach would be to speak personally with representatives from tertiary institutions involved with spectroscopy education and research. Canvassing for support was required, especially at those tertiary institutions that were traditionally “non-white” education centres, such as the Vista University campuses of Soweto and Mamelodi near Pretoria. The traditionally “white” education centres were not really a problem as they were already participating to a degree, although not regularly enough for it to be sustainable without any prompting from the society. The best strategy for the traditionally “white” centers would be increased and focused advertisement of the YSS and the latter groups to get more involved.

During March 1999, a very colourful poster was prepared advertising the YSS to take place in August of that year. It took three full days to meet with six lecturers from different institutions, or various departments at these institutions, in the Gauteng region. The cooperation was wonderful to experience. Responses from individuals prepared to actively participate exceeded expectations.

As many copies of the advertisement of the YSS as could be afforded to be printed, were distributed at these meetings. The lecturers gave their full support by circulating the information amongst their post-graduates and putting the posters on their notice boards. Some of these very colorful notices were posted to the institutions farther afield.

Since then and to date, the YSS has had unreserved support from the lecturers in spectroscopy, not only in the Gauteng region, but also at a national level wherever spectroscopy is practiced. Other provinces involved are the Western Cape branch and to a lesser degree, the southern Natal branch of the SASS. As a result of this success, the YSS changed from a biannual to an annual event.

Over the years, a lot of effort has gone into getting spectroscopists from industry also involved. A few young spectroscopists from various industries have competed at the YSS. Participation from industry is hampered by the need for industrial secrecy - we could have more involvement from this sector if it were not for this factor. Industrial chemists attend the YSS as delegates/spectators in sufficient numbers for us to be assured that, not only are they supporting the event by taking the time to spend a day listening to the presentations of other developing spectroscopist, they are also benefiting in the knowledge of the type of research the academics are doing.

Approximately 80% of spectroscopy done in industry is located in the Gauteng province. This is the reason why the YSS is usually held at one of the universities or technikons in that region.

Following on the success of the symposia held at the two Vista University campuses, the event has been held the Pretoria Technikon, Technikon Witwatersrand, University of Pretoria and this year, at the Rand Afrikaans University. The YSS has become well known in academic circles and is supported by most lecturers in the field of spectroscopy.

2.2 Modus operandi

As a result of its popularity, lecturers present at a symposium usually request to be the hosts for the following year. With this detail decided the previous year, liaison with the representative from the tertiary institution starts in January each year to set a date for the YSS to be in September/October of that year. This information is sufficient to start advertising the event for participants and delegates to attend.

A “call for papers” notice is prepared in poster format and circulated early, around February, each year to ensure that it is planned into annual academic programs of the various chemistry, physics and geology departments. Electronic and hard copies are circulated to the SASS members and to all the tertiary institutions nationally. This informs the academics and all the industrial spectroscopists of the deadlines and other relevant details. During the course of the next four months, a reminder of the meeting is circulated electronically to all members again. Any newsletters that are issued after February include the “call for papers” notice as well. Over the last four years there have been an average of fourteen students participating each year. The main criterion is that the topic of the presentation must be about spectroscopy.

During February and March and in liaison with the hosts, practical arrangements are finalized for the symposium day; i.e. decision for which local caterer, the lecture theatre and parking area to be used, hard copy and electronic versions of maps to the venue, etc.

As soon as the individual abstracts are submitted, they are electronically circulated to all the Executive Committee Members of SASS for evaluation and comment. On an individual basis, the student and lecturer/mentor is notified of the acceptance of the paper, with any recommendations for amendment included in that communication.

A panel of five judges is selected, of which at least three are academics. The judges may not be linked in any way to the research projects and the students presenting at the symposium. Two consistent judges presiding each year, are the managing director of PANalytical, SA and the President of the SASS. PANalytical traditionally are the main sponsors for the YSS.
To assist the adjudication and maintain a fair system, the judges are briefed in the use of a “score sheet” for each candidate. On the score sheet, 50% of the marks are allocated to the technical content of the paper delivered, 25% for format, audio-visual appearance, voice projection and confidence and the remaining 25% allocated to answering questions and adherence to the time slot on the program. An overall score is calculated for each presenter from the individual score cards recorded by the five judges. The top three candidates in the competition are awarded first, second and third prizes, which are described later under point 2.4.

The overall winner not only receives the first prize, but the Albert Strasheim floating trophy as well. The trophy is returned two weeks prior to the next YSS in the following year.

Students are prepared in advance to know what is expected on the day of the competition. In reply to acceptance of the abstract submitted, a copy of the score sheet is forwarded to each student and his/her mentor for preparation purposes. The target submission date of abstracts is one month prior to the event. From this information, a program is planned for the symposium. The format usually is to start by 08:30 and finish around 17:00, with a tea/coffee break midmorning, a 30-minute lunch break at midday and one afternoon tea/coffee break. A fair amount of student social interaction takes place during the breaks. Lecturers have the opportunity to talk to their counterparts at the other institutions. Delegates have an opportunity to meet with colleagues in spectroscopy and there is a lot of goodwill and talking amongst the contenders for the prizes during the social intervals.

The day is rounded off by a forty-five minute slot, which is reserved for either a motivational or instructive talk. Examples of the instructive talks are “How to prepare a good presentation” by emeritus professor James Willis and the “Mind-mapping” by Dr Jardin, a consultant, both of whom were willing to donate their time to be at the YSS. Another interesting and motivational talk was given last year by Mr Zwanda Ramadwa, namely, “Nurturing a culture of innovation and development in technology by bringing SET (science, engineering and technology) literacy to our nation”. This year a workshop was held during which students were asked to indicate what role they wanted to see the professional society playing in assisting young scientists with their development and growth in their careers.

Usually the audience is made up mainly of under-and post-graduate students and their lecturers. Many lecturers attend even if they do not have students participating in the event. Participants in the competition are BSc honors, Masters and PhD students, who are involved with research projects. Winners of the competition return with regularity to attend the YSS. Groups or individuals from industry and members of the SASS also attend. Students are admitted at special low fees of R20-00 to encourage as many as possible to attend.

Over the years the standard of presentation given at the YSS has increased considerably. In order to preserve the integrity of the event, a few basic rules have been developed by the Executive Committee. The set of rules are circulated at the beginning of the year along with the posters for the competition.

2.3 Integration of all spectroscopists
Inherent in what has evolved naturally into the current way the YSS is running, is the change that has come about in the composition of the participating tertiary institutions. Where, in the past, a special effort had to be made to get the institutions that were historically “non-white” to participate, this is no longer required. Delegates and representatives from these institutions have experienced over the last five years that they are an integral part of the whole. There is no need to call upon those lecturers to join those of longer standing and the traditionally “white” forum to attend the YSS.

The students are excellent promoters and advertise the competition amongst fellow students. The word-of-mouth advertisement has contributed greatly towards our success. Adjudication is based on performance and merit alone. In this process we have had presiders in the top level of first three positions being of any of our ethnic groups in the country and a good balance between male and female winners. A fair amount of networking is beginning to show between students in similar research projects, but living in different provinces. The winners of previous years and whom attend the YSS in the years after their successful competition, are naturally interested the achievements of those following in later years. There are signs that these winners are also naturally beginning to assume some leadership to help those developing in their wake.

2.4 Sponsors
In South Africa the support received from spectroscopy instruments and chemical suppliers is phenomenal. They still remain the major sponsors for financial needs that arise. As mentioned before, a large contributor to the YSS is PANalytical, SA who pay for the lunch and a substantial first prize. Examples of first prizes donated in the past are a video recorder, a mini high-fidelity sound system with CD player and tuner, etc. Another sponsor is Thermo-ARLabs. They sponsor an air ticket for any one of the students participating from the other provinces to go to Gauteng for the event. Each tertiary institution, which has hosted the YSS in the past six years, has sponsored the venue and coffee/tea breaks. Many of the lecturers give support to pay for the accommodation for their students.
when they have to travel from far destinations the night before the event. The SASS sponsors any other students for their traveling costs in order to be at the YSS. The SASS also sponsors the second and third prizes, book vouchers of R200-00 and R300-00 respectively.

3. Future Plans
It has already been mentioned that the last slot at the YSS this year was an interactive discussion with the students present on how they saw the role of the professional society in future assisting a developing spectroscopist in his/her career. A number of suggestions were noted for the SASS Executive Committee to investigate and implement where practicable. This action will take place during October 2003.

One aspect that has become evident during the period of preparation for and during the YSS is that the students are naturally gravitating towards leaders, and previous contestants are helping the upcoming spectroscopists with their presentations. A suggestion was made to the students that a representative is chosen at each tertiary institution to be the channel of communication linking from the students to the SASS and vice versa. In this way, we could dispatch our newsletters and advertisements of spectroscopy meetings taking place, to all students involved in science and spectroscopy research, regardless of whether they are members or not. The SASS would automatically form part of the networking at that level to the benefit of both parties. The appointment of a representative in the form of one of the more mature students at MSc or PhD level for spectroscopy amongst the post-graduates, would lead to graduate mentorships forming.

Rural science teachers are desperately in need of assistance, especially in previously disadvantaged communities. Spectroscopy graduates who are willing to get involved, could be included in the current outreach programs that are ongoing to address school groups about the importance of science education and the careers available to scientists. On these outreach programs, the students who spend time at the schools could help the teachers in their attempts to create parental awareness for learners who are showing the potential to follow a scientific career. In order to generate interest and motivation at school level, graduates could be encouraged to give talks in their own communities about their careers and their achievements.

Improved communications and assistance programs are instrumental in the SASS members being more informed of unemployed graduates. A natural spin-off of the improved networking in future will be added assistance for graduates seeking employment, where possible.

It is necessary to develop the wider involvement of the SASS in slow measures due to the voluntary and part-time basis on which the SASS Executive Committee operates. There are no individuals or SASS members who are able to focus on any of these activities of the society exclusively. All resources are from funds generated by arranging meetings, conferences, etc. However, it is believed that these activities that are to be developed during this next term of office will benefit the members and the field of spectroscopy. Evolving with the needs of the future generation of spectroscopists will also ensure that we keep the SASS alive and doing well in Africa.

I have included a copy each of a typical YSS program and the score sheet on the next three pages as examples of what is currently done for the YSS.

4. Acknowledgements
I want to thank the following organizations for their sponsorships for me to travel to the ETOP, 2003.
ICO – The International Commission for Optics
OSA – The Optical Society of America
APIE – The International Society of optical Engineers
# Young Spectroscopists Symposium

12 August 2003

## Evaluation of presenters

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Judge: 

Presenter: 

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Proceedings-ETuE2
Programme for Young Spectroscopist Symposium

08:30 – 08:50  Registration
08:50 – 09:10  Welcome – Prof Boeyens: University of Pretoria
Ms Janette Cawood: President SASS

Ms Maggi Loubser: Chairman
09:10 – 09:30  C. Canario, Technikon Pretoria
Atomic Absorption Spectrometric determination of Cd,Pb and Mn in urine with the Transverse Heated Filter Atomiser.

09:30 – 09:50  S. Mtongana, University of Stellenbosch
The structural elucidation of platinum(II) chelates of N-diisopropoxythiophosphoryl thioamide and N-diisopropoxythiophosphoryl-N-phenylthiourea by means of multinuclear NMR spectroscopy.

09:50 – 10:10  A. du Plessis, University of Stellenbosch
A tunable pulsed Raman laser for IR spectroscopy.

10:10 – 10:30  N. Mhlahlo, University of Cape Town
Analysis of Spectroscopic observations of the cataclysmic variable, TX Col.

10:30 – 10:50  S Govender, University of Cape Town
Lead concentration and isotopic composition by mass spectrometry and their implication for anthropogenic components at farms in Philippi, W Cape – a pilot study.

10:50 – 11:15  TEA

11:15 – 11:35  M. Lumka, Vista University, Soweto Campus
X-Ray Fluorescence analysis of aerosols from Venda and Bethlehem.

11:35 – 11:55  J. Mnisi, Vista University, Soweto Campus
Development of a novel method for slag sampling employing XRF spectrometry.

11:55 – 12:15  S Madileng, Vista University, Soweto Campus
Theoretical Structural and the Vibrational Spectral predictions of the Boron Iodide Dimeric Species.

12:15 – 12:35  P. Swafo, University of South Africa
FT-Raman spectroscopic study of hydrogen bonding in water-methanol mixtures.

12:35 – 12:55  M Legodi, University of Pretoria
Raman Spectra of clays and pigments used in ancient artefacts.

12:55 – 13:30  LUNCH

13:30 – 13:50  N. Krusberski, Rand Afrikaans University
The evaluation of different calibration strategies using emulsions for wear-metal-in-oil analyses.

13:50 – 14:10  S. Jansen van Vuuren, Rand Afrikaans University
The simultaneous separation and determination of Cr(III) and Cr(VI) species by ion chromatography – inductively coupled plasma – optical emission spectrometry.
14:10 – 14:30  Z. Foldvarl, University of Pretoria  
Determination of the stereoselectivity of Sharpless epoxidation/kinetic resolution of (3RS)-7-
[(tert-butyldimethylsilyl)oxy]–hept-1-en-3-ol by nuclear magnetic resonance spectroscopy.

14:30 – 14:50  A. Whaley, University of Pretoria  
Selective ionisation techniques for mass spectrometry.

14:50 – 15:20  TEA

15:20 – 15:30  Prizegiving

15:30 – 16:30  Mr Z. Ramadwa,  
Nuturing a culture of innovation and development in technology by bringing SET  
(science, engineering and technology) literacy to our nation

16:30 – 16:45  Conclusion and Acknowledgements – Ms Janette Cawood
The optical mouse as an inexpensive measurement device

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Abstract: The optical mouse is an inexpensive and easily available device that interfaces directly to a computer. Here, the viability of this device in optical metrology is demonstrated. Application in a wide range of student experiments is anticipated.

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OCIS codes: (120.4640) Optical Instruments; (120.3940) Metrology

1. Introduction
Sensing and measurement are the cornerstones of experimentation [1] in science and engineering education. The sensing and measurement of translation is a fundamental endeavor in this respect. However, experiments based on translation using optical sensing are generally expensive to assemble. This has unfortunately resulted in a relative dearth of such experiments. The availability of a cheaper device offers interesting vistas.

Until recently, the operation of computer mice had been based almost exclusively on the rolling ball principle. Popularly called the mechanical mouse, it houses a rubberized ball that rolls according to the planar movement imposed on the mouse. Two rollers located within the mouse are in constant contact with the rubberized ball. One of the rollers detects for motion in the x-direction whereas the other detects for motion in the y-direction. Quite naturally, the mechanical mouse suffers from the problems of wear and dirt accumulation over time. For this reason, it is common to find them incapable of registering movement after several months of heavy usage. In 1999, Agilent Technologies unveiled the first optical mouse that was immune to the problems of wear and dirt accumulation. With resolutions currently reaching 0.03175 mm, optical mice are gradually replacing their mechanical predecessors as the pointing device of choice in computers. Due to the economics of large volume production, the cost of an optical mouse is extremely low. Currently, it is possible to acquire a reasonably good quality unit for as low as US$20.

Here, the viability of the optical mouse in measurement applications is demonstrated. These applications range from static, quasi-static to dynamic forms.

2. Incorporation of the optical mouse in translation-based experiments
Two translation-based experiments were devised to illustrate the possibility of incorporation of the optical mouse as sensing device.

2.1 Comparison of translation with an opto-mechanical stage
In this experiment, a xyz translation stage (Newport M-460A-XYZ model) is used. The resolution of the translator along each axis is 10 micrometers. The test surface is attached to the vertical faceplate of the translator (Fig. 1). In the experiment, three types of surfaces were applied for testing: a diffusely white painted plate, a plexiglass sheet, and a square mirror. Each was meant to represent an opaque, transparent, and reflective object respectively. An optical mouse with a resolution of 0.0635 mm was employed for testing. On the computer, any imaging software (e.g. Windows Paint) may be used to determine the mouse’s position. In the experiment, the value of z (Fig. 1) represented the position that the optical mouse was placed from the object’s surface. For each setting of z, displacements in the x and y axis, as registered in the computer due to the optical mouse’s movement, were compared with actuations from 0 to 1 mm at intervals of 0.05 mm on the xyz translation stage. The same procedure was repeated for values of z from 0 to 1.5 mm at increments of 0.25 mm.
2.2 Measuring the viscoelastic response of polyethylene

A very simple demonstration of viscoelasticity can be carried out by attaching a weight to polymer film and watching it extend over time. For quantifiable data, a rule may be stationed beside the polymer film to measure the extension. Such an approach will likely give very coarse measurements that will make it difficult to ascertain important parameters such as the relaxation time. Improved measurements may be obtained via an ultrasonic motion sensor [2] attached to a universal laboratory interface [3]. Such a sensor and interface can be expensive.

In this experiment, the polyethylene film is properly fixed to the top section of a loading fixture (Fig. 2). The lower section of the loading fixture is moveable and comprises an opaque guide. An optical mouse is arranged beside the loading fixture to sense movement of the reference surface. The reference surface should be able to move freely. This can be confirmed by pulling the opaque guide up and down slowly. The gap between opaque guide and optical mouse should also be kept within 1mm; otherwise the optical mouse will fail to register any movement. Once these precautions are adhered to, a weight can be hung at the bottom of the loading fixture. The extension of the polyethylene film is recorded at fixed time intervals (typically 10 seconds) for a certain period of time (typically 5 minutes) using the stopwatch. On the computer, any simple software may be used to determine the mouse’s position.
3. Results and Discussion

In the experiment to compare translation with an opto-mechanical stage, the optical mouse was found to only able to register displacements when the diffuse white painted plate was used as the test object. This result simply confirms that transparent and reflective objects are unsuited for displacement measurement using optical mice.

Fig. 3 shows the graphs of x and y direction displacements recorded using the optical mouse and plotted against displacements introduced by the xyz translator for values of $z = 0$ and $z = 0.25$mm. From visual inspection, it can be seen that a positive trend exists between the displacements detected on the optical mouse in relation to the translations introduced. No measurements could be obtained when $z$ exceeded 1.25mm. This is likely to be caused by complete defocusing. Together with the observed linear trend, this result implies that the optical mouse is generally suited for two-dimensional displacement measurement provided that $z$ does not exceed 1.25mm.

![Graphs of x and y direction displacements recorded using the optical mouse against displacements introduced using the translator for (a) $z = 0$ and (b) $z = 0.25$mm.](image)

The elongation behaviour of low-density polyethylene film in relation to time is given in Fig. 4. The three films had the same dimension but were obtained from different manufacturers. The trends of the curves follow that reported in literature [4]. This demonstrates the ability of the optical mouse to serve as a displacement sensor in actual engineering applications. Whilst the films displayed clear viscoelastic responses, their displacement amplitudes were clearly different. Such differences can be used to engage in discussions of contributing factors such as processing. The contribution of processing factors is well studied in low-density polyethylene processing [5-6].

It should be noted that the manner in which the experiment was set up prevented movement in the $z$-direction whilst the film was loaded. Hence, the $z$ distance limitation mentioned earlier was not operational in this experiment.
Fig. 4. Plot of elongation against time of the experiment to illustrate the viscoelastic response of polyethylene

4. Conclusions

The optical mouse was applied in two experiments; one to compare translation with an opto-mechanical translator and another to sense the viscoelastic response of polyethylene. Its efficacy was proven in both cases. This portends the possibility of creating a wide range of low-cost but engaging experiments for students.

5. References


Capacity building in Optics and Photonics by international collaboration

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Abstract: A project seeking to improve capacities in teaching Optics and Photonics in university introductory physics courses and benefit teachers in developing countries will be implemented by international collaboration. Active learning modules in Optics will be based on available resources and inexpensive materials. Most workshop facilitators will come from developing countries.

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OCIS codes: (000.2060) Education; (120.4820) Optical Systems

1. Introduction

UNESCO is the only international organization with a mandate in capacity building in science and technology. Within this context, UNESCO has existing programmes in physics, mathematics, chemistry and the life sciences. Projects and initiatives in university physics education are implemented under the physics programme. It is within this framework that UNESCO recently launched a project aiming primarily to improve capacities in teaching optics and photonics in introductory physics courses in the university.

The purpose of this paper is to discuss the work of UNESCO in promoting physics education in developing countries and how this experience is applied to optics and photonics.

UNESCO usually implements its projects in physics education through international collaboration, with the participation of as many countries as practically possible. UNESCO fosters capacity building for physics research through its continuing support of the Abdus Salam International Centre for Theoretical Physics (ICTP), well known for its activities organized for the benefit of physicists from developing countries. As well, UNESCO was instrumental to the establishment of the International Commission of Physics Education (ICPE), otherwise known as Commission 14 of the International Union of Pure and Applied Physics. For the specific purpose of promoting physics education, regional physics education networks were established under the auspices of UNESCO in the 1980’s- the Asian Physics Education Network (ASPEN), the Arab-African Physics Education Network (ARAPEN), and the Latin American Physics Education Network (LARAPEN). For more than 10 years, these networks saw the involvement of many countries in various UNESCO activities in physics education. Of these networks, only ASPEN survived the changing and difficult times in the different regions of the world.

In 1990, UNESCO launched a project called University Foundation Course in Physics (UUFCP) [1], which aimed to strengthen through international cooperation, university teaching at the introductory level in physics. It proposed to develop a new approach for the introductory physics course by bringing together expertise from developing and developed countries. It was designed to assist universities, especially those in developing countries, in their efforts to improve the quality, effectiveness, and relevance of the introductory physics courses. While emphasizing the need for more laboratory work and topics on contemporary physics, UUFCP recognized that not all topics can be taken up with equal rigor and effectiveness. Through ASPEN, with participating experts from China, India, Japan, Australia and the Philippines, the project took off in Asia and resulted in the production of a textbook, modules on selected topics in contemporary physics, laboratory manuals, instructional materials on video and computer simulation software.

UUFCP is significant because it was a pioneering effort to break away from the traditional approach in the way introductory physics was taught. Moreover, it enabled different countries, through international collaboration, to develop their own instructional materials.

With support from UNESCO, ASPEN activities have been organized to respond to the following problems in university physics education [2]:

1) The lack of creativity and innovation in the way physics is taught, resulting in boring chalk-&-talk classroom lectures and the students losing interest in physics;

2) The need for upgrading and providing foundation to the conceptual knowledge of many physics teachers and lecturers, especially those in developing countries.
ASPEN has responded to these problems mainly through conferences and workshops on topics including undergraduate laboratory, use of demonstrations, importance of conceptual understanding, and the use of computers in physics experiments.

2. Active learning in Physics

Since 1996, UNESCO and ASPEN organized more activities featuring hands-on workshops and innovations resulting from physics education research mainly from physics departments in the United States. In particular, the active learning technique has been the topic of recent workshops, as well as that of curriculum material development, building regional capacities in the use and application of the method. Workshops have been run in Laos, Malaysia, the Philippines, South Korea, Sri Lanka, Vietnam, and very recently, in Ghana in Africa. Fig. 1 shows a typical workshop in Sri Lanka. Moreover, with UNESCO support, active learning modules on topics in mechanics have been developed and compiled for free distribution [3]. An illustration from one of these modules is reproduced in Fig. 2.

![Fig. 1. An active learning workshop in Sri Lanka.](image1)

![Fig. 2. An active learning module on angular momentum: what happens to the rotating wheel if one of the strings is cut?](image2)

The active learning method, also known as ‘interactive engagement,’ cares about the student and her/his learning style and endeavors to match the teacher’s strategy with the student’s learning style. The active learning environment is characterized as student-centered and activity-based using computers and equipment. Lectures are kept to a minimum. Students are actively engaged or participating actively in the learning process. When students, working in groups, are actively engaged with class experiments, for example, and guided to make observations, experiment, make mathematical descriptions, and construct theories, they develop scientific reasoning skills and learn the underlying principles and concepts [4]. On the other hand, the instructor prepares the learning environment,
and through activities, questions, discussions, guides students through the reasoning necessary to construct concepts, then apply them to real-world situations [4]. Finally, assessment and evaluation are considered an essential part of the active learning method [5]. It is important to determine using suitable instruments how well the students are learning physics concepts.

Active learning in physics is being developed through physics education research, applying the rules of evidence of experimental physics, with the purpose of promoting active mental engagement of students in the process of learning physics. Much of the research has focused on the transformation of passive instruction in large lecture halls with large numbers of students, the usual setting of many physics classes. Interactive engagement has been shown to have successfully resulted from, to mention a few, the use of short lectures interspersed with conceptual multiple-choice questions fostering student-instructor interaction [6], the use of interactive lecture demonstrations supported by real-time microcomputer-based laboratory tools [7], the use of materials with carefully structured experiments, exercises and questions that guide students step-by-step through reasoning in constructing concepts [8], and the use of a series of related activities designed to follow a learning sequence and using apparatus and computer tools [9]. The research-based development of curriculum has led to the development of standardized assessment instruments designed to probe conceptual understanding. Some of these tools are notably the Force Concept Inventory (FCI), the Force and Motion Conceptual Evaluation (FMCE), and the Conceptual Survey of Electricity and Magnetism (CSEM) [5].

In an active learning environment, the instructor gives up her/his role as the source of all information in the classroom to give way to being guide and facilitator [10]. This is perhaps the biggest challenge there is in adopting this method of teaching since most teachers must have been taught in traditional passive learning environments. On the other hand, the students cease to be mere receivers of information and are no longer subject to mindless note-taking in the classroom [10]. A carefully designed instrument for assessment of student learning is an integral part of the learning process [8]. This assessment tool is different from the usual examination problems requiring manipulation of formulas or questions that can be answered on the basis of memorization.

UNESCO and ASPEN promote the active learning method, especially in developing countries, for a number of reasons. Together, UNESCO and ASPEN have consistently promoted the use of laboratory and hands-on activities in physics classes. Research results show that implementing an activity-based curriculum and mentally engaging students in class can promote conceptual understanding. The method encourages the physics instructor to do research and enable her/him to devise and find creative ways to improve her/his teaching and student learning. This is one research area where physics teachers from developing countries can make valuable contributions. Physics education research may provide the key to student learning in physics and needs to be widely fostered by the international physics community.

3. Training trainers in Optics and Photonics

By promoting the adoption of the active learning method, UNESCO aims to improve capacities in teaching optics and photonics in introductory physics courses in the university.

The project is focused on optics and photonics because it is one of the few experimental physics areas that have been found to be relevant and adaptable to research and educational conditions in many developing countries. It is one research area that is closely linked to industrial applications, and has been found useful in a number of developing countries, notably in Southeast Asia and Africa. Optics and laser research laboratories can be found in Indonesia and the Philippines, to name a few, as well as in Ghana, Tunisia and Senegal. Experiments in optics and photonics are relatively inexpensive and cost-effective to set up and can be implemented in a modular manner. Most often, space and power requirements are reasonable and affordable. Moreover, with the advances in optical communications and other laser applications in industry and medicine, some level of local research collaboration with industries and hospitals has become possible. Furthermore, opportunities for regional research collaboration exist for photonics applications to environmental problems of regional scope. In general, the challenge for research for experimental physicists in developing countries is finding an application relevant to the local needs and existing conditions, and the corresponding logistical support.

The project is proposed for the benefit of physics teachers from developing countries. It hopes to encourage them to teach better the optics part of the introductory physics course by drawing examples from local research activities and inspire students to do projects and pursue further studies in the field. Fostering understanding and appreciation of optics in high school and the early years after would also lead to better training of technicians. Consequently, this may lead to an increase in public understanding and interest in the important benefits derivable from applications of optics and photonics. In the long run, public realization of the significance of local optics and photonics research may open up opportunities for funding and logistical support.
3.1 Objectives of the project

The project seeks to promote the teaching of optics in the level of introductory physics in the university. The project encourages physics teachers to take up topics in geometrical and wave optics and use the active learning method in the process. Teachers will be trained to become active learners themselves. Active learning workshops will enable teachers to design and prepare various class activities, such as simple experiments, demonstrations, exercises, using available materials and equipment. Teachers will practice making predictions and formulating questions that will probe and guide students through the reasoning necessary to explain observations and experimental results. The project seeks to promote physics education research by using the teacher-designed activities to investigate student understanding of basic optics principles and concepts. Teachers will be encouraged to do literature research and be familiar with background information and published research results, as well as document their own procedures and results.

Teachers will be trained to formulate and use instruments to assess student understanding. Most of these tools are qualitative questions that are administered before (pretest) and after (posttest) a topic or a course is taken up with the students. In his comparison of the effectiveness of traditional versus interactive engagement methods in mechanics, Hake [5] used the normalized gain (gain/maximum possible gain). While the normalized gain may provide a good measure of the effectiveness of the teaching strategy used, Hake cautions that the normalized gain does not give a definitive assessment of the overall effectiveness of the method. While some research results from work done on probing conceptual understanding of optical principles have been published, a standardized assessment instrument on optics still has to be put together.

Finally, the project seeks to develop through physics education research creative and innovative teaching and learning materials in optics and photonics, as well as instruments for assessment. Teachers will be encouraged to document their own procedures and results, conduct systematic investigation of student understanding of optics by designing activities and formulating probing questions with clear objectives and expected outputs, formulate appropriate tools and assess the effectiveness of the method, and use the results to improve further the application of the method. The process may lead to the identification of learning difficulties and misconceptions, which can be analyzed and addressed through research.

Training teachers to become active learners and apply the method in their teaching should provide foundation to their own conceptual knowledge. Hestenes [11] defines “conceptual learning” as opposed to “rote learning,” which depends on memorization of facts and formulas, and explains it in several ways.

Conceptual learning is a creative act. The teacher who understands well the basic optics concepts will be able to design varied class activities and formulate engaging guide questions. The student who has a good grasp of basic optics concepts will enjoy and look forward to doing class activities and pursuing projects. An active learner will therefore foster creativity and innovations.

Conceptual learning is systemic. Concepts derive their meaning from a coherent conceptual framework. Interference and diffraction of light are defined within the context of the wave model of light. Active learners should be able to see and understand the interrelationships among physical quantities within the appropriate framework.

Conceptual learning is contextual. The active learning method will be introduced in developing countries in ways recognizing this fact.

3.2 Active learning in Optics

A reference database is being compiled of what is available in the literature on the topic. This section presents two examples from literature of physics education research results in optics.

The first example is taken from the project Constructing Physics Understanding in a Computer-Supported Learning Environment (CPU) and focuses on image formation by converging lenses [12]. Research has shown that students have difficulty understanding the following ideas:

(1) From each point source, light travels outward in all directions.

(2) An extended light source can be considered as a sequence of source points.

(3) In the image formation process light spreading out from each point on the source passes through the converging lens and comes together at a unique point called the image point.

To help students better understand these ideas, CPU curriculum materials and simulators were designed. Students can use the CPU light and color simulator to construct set-ups with a light source, lens and screen that match the laboratory experiments. The simulator can reproduce whatever appears on the screen and generate light ray diagrams.
In the actual experiment, a MiniMaglite flashlight is used to approximate a point source in front of a lens and a screen. On the simulator, a point source is used with a light ray spray tool to generate light rays emerging from the point source through the lens that focuses the light rays on a unique point on the screen. In the laboratory set-up, when the screen is moved closer or further from the lens, students can observe on the simulator that blurring images correspond to the screen intercepting light rays before or after converging to a single point. Several MiniMaglites in front of the lens and screen are used to enable students to imagine a sequence of point sources. The simulator displays the analogous situation. Finally, students do both laboratory and simulator experiments with an extended light source. As the student traces points on the extended light source from one end to another, he can see the corresponding image points mapped out on the simulator. The student then directly observes that each image point corresponds to a point on the source.

The Physics Education Group at the University of Washington has been engaged in a long-term investigation of student understanding of geometrical and physical optics. The second example is taken from a paper reporting their investigation of student understanding of double-slit interference of light [13]. The context for the group’s research is during a 50-minute tutorial attended by 20-24 students working collaboratively in groups of 3 or 4. Designed to supplement lectures and the textbook, tutorials emphasize constructing concepts, developing reasoning skills, and relating physics formalism to the real world. Each tutorial session consists of a pretest, worksheet, homework assignment, and a posttest.

In investigating student understanding of double-slit interference of light, interviews and responses to questions indicate that it is necessary to develop a basic wave model for the phenomenon. To do so, exercises with the ripple tank were used to demonstrate interference properties of water waves. Waves in the ripple tank are easier to observe than light waves and make it possible for the students to visualize wave fronts. Through interviews and pretests, student difficulties in understanding the aspects of the problem are exposed. With respect to developing a wave model for double-slit interference of water waves, students had difficulty relating interference to path difference, and understanding how principle of superposition applied to water waves. The tutorial is then designed to guide the students to recognize the problem and help them go through the reasoning required to resolve the difficulty. In this case, the students are given a diagram of two overlapping sets of concentric circles representing wave fronts due to two point sources of water waves, and tutorial questions help them analyze the phenomenon step-by-step. A homework assignment reinforces their observations in the tutorial exercises and helps the students derive and apply formulas for locating nodal lines and lines of maximum constructive interference.

The next step is to establish the analogy between superposition in water and in light waves. This is done by addressing the failure of the students to relate a sufficiently narrow slit to a point source. A tutorial exercise is designed to make students arrange sponges in a shallow pan of water to form slits of various widths. They generate parallel wavefronts and observe what happens when the waves pass through sufficiently wide and narrow slits. The tutorial then guides the students in making a proper analogy between interference in water and in light. Moreover, the tutorial on double-slit interference includes an exercise designed to help students recognize that geometrical optics cannot be used to make predictions about light passing through very narrow slits. Finally, using a pretest to expose the difficulty, tutorial exercises are used to help students recognize how a two-slit interference pattern is affected by changes in the slit separation and other parameters of the optical system.

The paper goes on to describe the work on extending the model to multiple slit interference, single slit diffraction, and so on. The authors emphasize that the improvement gained by the students in understanding the wave model for double slit interference of light is reinforced by extending the model to other cases and building on their experience from the double slit case.

3.3 Implementation of the project

The project will be implemented by an international working group whose members have expertise in optics and photonics and in the active learning method. As a project proposed for the benefit of physics teachers in developing countries, it is important that they are well-represented in the working group. Building on its experience of continuing cooperation with ASPEN, UNESCO has begun to promote active learning in other regions, particularly Africa, in order to address similar issues in physics education. ASPEN is expected therefore to play an active role in the project, and so will physics teachers from Africa. ASPEN representatives in the working group will come from countries that have given efforts to adopt the active learning method in their physics classes. They are ASPEN members who have designed demonstrations and simple experiments and are applying them in their physics classes. As the UNESCO institute promoting physics research and providing consistent support to optics and photonics researchers in developing countries, ICTP is involved in the project implementation. The international optics community is represented in the project working group by one OSA and one SPIE officers. UNESCO is providing
seed funds for the initial implementation. While the project working group is kept deliberately small in size, participation of more people in the implementation will be invited in due time.

The project has started by providing modest support to ASPEN members from the Philippines to develop active learning modules in selected topics in optics. These curriculum materials will make use of simple optical elements and other inexpensive components, as depicted in Fig. 3. The modules will be used in the project to introduce and demonstrate the active learning method to the project working group, and to initiate research in the Philippines of student understanding of basic optical principles.

![Fig. 3. Some simple optical components to be used in active learning curriculum development.](image)

The project focuses on the active learning method, the student-centered, hands-on, minds-on approach to introductory physics teaching. Teaching optics the active learning way implies the use of a variety of class activities where the students are actively engaged and the instructor acts as guide and facilitator. How different will these teaching and learning materials be from those that have been described in the literature? McDermott [8] emphasizes that a lot of time and effort goes into development of curriculum that is effective and can be used by different instructors. Her advice is “to take advantage of existing curriculum that has been thoroughly evaluated.” By considering the diverse needs and conditions existing in target countries, learning and teaching curriculum in optics are to be developed based on available resources and the cultural context. Materials already developed and evaluated elsewhere within a specific context will certainly be valuable. However, they have to be adapted to existing conditions if they are to be effectively applied in a different setting. The outstanding work of the pioneers of physics education research serves as a model to be followed by other physics teachers. Their commitment and hard work are a source of inspiration and serve to awaken the inherent creativity of many physics teachers, especially those from developing countries.

While assuming that the project beneficiaries may have been taught in passive learning environments, there are many factors to be considered in context-based active learning curriculum development. A few are enumerated as follows:

1) the way the introductory physics course is taught at present in universities; textbooks and references available; language used in instruction; is the local language used in schools and universities?
2) state of physics teaching laboratories; available materials and equipment, including computers, as well as repair and maintenance facilities; feasibility of local acquisition of new equipment, by purchase or fabrication
3) condition of buildings and rooms; space available for physics teaching
4) number of students, men and women, in physics classes at various levels; their science background prior to university; language/s spoken
5) local efforts to improve physics teaching
6) level of government or public support for science education and research
7) salaries and compensation for teachers

Most workshop facilitators and resource persons for the project will come from developing countries and more of them will be trained, as was done in Fig. 4. The trainees in the workshop shown in the figure were presented with all kinds of available devices and materials, both computer and non-computer-based.
Optics trainers’ training courses are expected to be similar to previous UNESCO-ASPEN active learning workshops where modern optical devices, when they are available, can be used together with traditional equipment and inexpensive materials. Training organizers will be encouraged to cooperate with local optics and photonics researchers and take advantage of their expertise and experience. Optics teachers will be encouraged to draw examples from local research activities. Various kits of simple optical components will be tried out and evaluated. Training participants will be given time to familiarize themselves with, play and experiment with the equipment, to enable them to design and develop teaching and learning materials.

The following activities are foreseen as important components of the project implementation:
1) Preparation of active learning trainers’ training syllabi, materials and equipment in optics and photonics
2) Trainers’ training workshops in different countries
3) Developing teaching and learning materials (kits) adapted to different conditions in participating countries.
4) Developing instruments for assessment and evaluation in optics and photonics.

4. Challenges to the project [2]

A challenging project is always worthwhile to pursue. The most important challenge of all is learning to become an active learner. The shift from a passive learning environment to an active learning one is not easy for both student and teacher. For the teacher, he/she needs to give up lectures and give way to being a guide and facilitator. For the students, they need to appreciate the involvement required from them.

Applying the active learning strategy requires advance planning and preparation of the instructional and learning materials, on the part of the instructor, and reviewing material and doing homework regularly, on the part of the students. For some students and teachers, this may seem an unreasonable demand for time and energy.

An activity-based curriculum takes much time to implement in the classroom. This implies that less topics can be covered in depth within a given term or semester. This may seem frustrating to most teachers who feel that a complete introductory optics course should cover all topics in geometric and physical optics with equal rigor and depth. The issues of coverage in optics should be discussed as a community including both teachers and researchers.

Equally daunting is the task of adapting the technique to the characteristics, the needs and the problems of the situation and the people involved. The active learning method should be applied in consideration of the varied contexts of its users. Adaptation calls for creativity in implementing the strategy, sensitivity towards needs and difficulties, and flexibility in handling unfamiliar situations. Active learning was first introduced to ASPEN with the exclusive use of computers and computer-interfaced sensors and measuring devices. Being characterized by great diversity, Asia has universities and physics departments endowed with facilities ranging from the most advanced to the oldest and most traditional. Colleagues from less endowed universities only had traditional equipment. For them, the ASPEN active learning team developed non-computer-based interactive lecture demonstrations, and proved that traditional physics equipment and inexpensive locally-available materials can be used to promote conceptual understanding.

It must be recognized that an activity-based curriculum has greater demands for resources than the traditional lecture-based course. It is not easy to find these resources.

It is important to have a group of resource persons coming from a certain region that identifies with the workshop beneficiaries and understands the conditions in the region. Having a regionally indigenous resource group
would encourage ownership of the strategy and quickly build confidence among colleagues. Training resource persons may prove to be a great challenge, since the number of physics teachers inadequately trained in the discipline is quite daunting. Trainers’ training workshops then should be regarded as an opportunity to upgrade the conceptual knowledge of many university and secondary school physics teachers and lecturers.

The cultural diversity in a given region lends itself to an important issue that is reflected in varied learning styles of students. For example, while students in the Philippines can be easily encouraged to come forward and discuss the results of their measurements, this may not be necessarily so for students in South Korea. This is a definite challenge to the instructor, who is expected to be creative in exploring ways of actively engaging students through class activities and discussions.

Finally, there is a need to keep up with new developments in physics education research and share experiences, information and materials. Primarily, this implies the need to access journals and research literature, and contribute articles. This is part of the bigger issue of dissemination of scientific knowledge to developing countries. On one hand, there is a need to provide access to the increasing number of research papers addressing different issues in physics education. On the other hand, as physics teachers succeed in adapting innovations, produce materials and gain experiences, they will find the need to document their work and results, and share them with fellow researchers in the field. The physics teachers from developing countries, the beneficiaries of this project, should be prepared for this eventual development.

Some of the challenges mentioned are a consequence of the pervading traditional culture in physics teaching and are expected to be resolved, as the project progresses and the overall situation of physics education improves.

Many of these challenges may be overcome through collaboration and networking. Physics teachers can work together, exchange ideas and experiences, learn from one another, and together endeavor to find the many resources required in achieving the paradigm shift in physics education.

5. References

Integrating Writing into the Optics Curriculum

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Abstract

In response to a need for interactive learning, we designed a physical optics course that incorporates writing-to-learn principles and allows students to meld in-class theory with real-world practice. Students "published" their papers on the open-access web. This exercise necessitated that students understand principles sufficiently to simplify complex topics for a broad general audience.

Advanced courses in physical optics require problem-solving skills that may include calculus, complex numbers, trigonometry, algebra, and graphical representations. Abstract concepts are described -- sometimes to explain commonly experienced phenomena. Rather than supplementing empirical knowledge, students often supplant it with an analytical version of nature. In large part this abandonment can be attributed to the lack of qualitative information covered in these courses. Academic institutions expect the syllabus to be densely packed with technical topics, leaving little class time for integrating analytical and qualitative knowledge. Many believe students would be better prepared to master their discipline if they had experience assimilating both types of information [1,2].

Given limitations of the syllabus and the schedule, a natural solution is to find sufficiently interesting projects for the students to explore qualitative aspects on their own. We have found that this goal can be achieved while also satisfying other missing elements such as writing, information and technical literacy, communication, and teamwork. A solution is to assign a writing project that describes to an educated audience either a physical phenomenon or to report on the life and science of a noteworthy scientist or engineer [3]. The students not only use the World Wide Web for researching their topic, thus gaining an exposure to information literacy, but they also publish their report as a web page, thus providing a very real and wide audience. This latter requirement gives the students a greater stake and sense of ownership in the project. Teamwork skills are honed as well, owing to the students’ limited technical knowledge of searching and writing for the web.

This course, called “OPTI 310 – Physical Optics I” is taught in the fall semester at the University of Arizona Optical Sciences Center. The nominal student population is 30 mostly junior-year students majoring in an ABET-accredited Optical Sciences and Engineering program. The syllabus lists such topics as wave theory, reflection and refraction, polarization, interference, Fourier analysis, and Fraunhoffer diffraction. There are roughly 41 lecture periods and 4 in-class exams and one pre-test on the first day of class. Two or three computer-based computational type projects are assigned during the semester. The most significant writing project is a term paper, which is the subject of this communication.

The writing assignment requires each student to select as a topic an optical phenomenon. The primary objective is for the student to communicate the nature of this phenomenon in terms of physical optics principles to an advanced high school or college freshman. The desired report length is an equivalent of two or three pages of typed double-spaced text, discounting figures, equations, and references. A typed hard-copy report, however, is not allowed.
Rather, the students must publish their report on the world-wide web, thereby allowing anyone to access the document. Milestones are set during the semester and one or two class periods are devoted to library search methods and elements of writing. Feedback from the professor is provided after completing each milestone.

Roughly half the students have no experience developing a web page. To gain this knowledge students must consult their peers or other information resources. Typically students team up with their OPTI 310 classmates to reach an adequate level of competency in this area. This sink-or-swim approach therefore encourages and rewards teamwork. There are a surprising number of ways a student can approach web writing; for example, free sites that sport pop-up advertisements, software packages (Netscape Composer, Dreamweaver, Front Page, Bbedit, etc.), and html translators in software products such as Microsoft Word and Powerpoint. In retrospect we found it necessary to limit which approaches to allow. We also found it advantageous to restrict the report to a single web page with no links to subsequent pages.

Students reported in anonymous course evaluations that they appreciated an opportunity to develop a more complete understanding of a topic and to exercise communication skills that demonstrated to the world their level of mastery. We believe that the act of writing, with its challenges in the art of decision-making, gave students practice in the “uncertainty” that is a universal component of “all engineering design” [4]. As writers, the students had to exercise judgment and make decisions in a context very different from the dichotomous right or wrong arena of problem solving. Finally, the idea that science was again living, that it spoke a language beyond mathematics helped stoke the exhausted flames of scientific passion at the mid-point of the students’ undergraduate experience.

We note that science faculty are sometimes reluctant to teach with writing for several reasons. Some fear that they need specialized knowledge in grammar or the teaching of composition; others fear that bringing writing into the science classroom will detract from the time devoted to content. However we believe faculty are often frustrated when they teach material that is soon forgotten (e.g., the meaning and use of equations, technical definitions, or proper approaches to particular problems). We were determined to provide an assignment with a lasting impact, and something that the students could share with their parents or friends (and indeed the world). Through writing, each student had the opportunity to develop an integrated understanding of a topic, thus enhancing the ability to recall the material at a later date. Furthermore the act of publishing the work instills a sense of pride and ownership, and a tendency to do well and show it off. Our experiences confirmed what Bean points out in Engaging Ideas [5], namely, that because we were teaching with writing, the writing became a tool with which we could actively engage students. Furthermore, because each student’s web pages was available to the other students, they all gained experience forming a knowledge community. Learning was allowed to become dynamic and student-based and less reliant on a single authority figure.

In addition to the many benefits of integrating writing into a course curriculum, it is important to note that more than just individuals benefit from this type of course assignment. In 2000 ABET revised its accreditation standards to focus on demonstrated student learning rather than course offerings and statistics. A course that integrates writing requirements, such as OPTI 310, helps to demonstrate how students meet several of the learning outcomes set forth under ABET Criterion 3, XXX. The Learning Outcomes are listed in Table. I. Besides contributing toward the successful demonstration of the ABET Criterion, the course assignment also helps to meet the Information Literacy Competency Standards adopted in January 2000 by the American Association for Higher Education (AAHE) and the
Association of College & Research Libraries (ACRL). In today’s society of information overload, the standards, listed in Table II, are aimed toward the development of information-smart, life-long learners.

### TABLE I
**ABET CRITERION 3 LEARNING OUTCOMES**

Programs must demonstrate that their graduates have:

| 3a   | An ability to apply knowledge of mathematics, science and technology |
| 3b   | An ability to design and conduct experiments, as well as analyze and interpret the data |
| 3c   | An ability to design a system, component, or process to meet desired needs |
| 3d   | An ability to function on interdisciplinary teams |
| 3e   | An ability to identify, formulate and solve engineering problems |
| 3f   | An understanding of professional and ethical responsibility |
| 3g   | An ability to communicate effectively |
| 3h   | The broad education necessary to understand the impact of engineering solutions in a global and societal context |
| 3i   | A recognition of the need for and an ability to engage in lifelong learning |
| 3j   | A knowledge of contemporary issues |
| 3k   | An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice |

### TABLE II
**ACRL INFORMATION LITERACY COMPETENCY STANDARDS FOR HIGHER EDUCATION**

| Standard 1 | The information literate student determines the nature and extent of information needed. |
| Standard 2 | The information literate student accesses needed information effectively and efficiently. |
| Standard 3 | The information literate student evaluates information and its sources critically and incorporates selected information into his or her knowledge base and value system. |
| Standard 4 | The information literate student, individually or as a member of a group, uses information effectively to accomplish a specific purpose. |
| Standard 5 | The information literate student understands many of the economic, legal and social issues surrounding the use of information and accesses and uses information ethically and legally. |

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Curriculum, program, and infrastructure development for Bachelor of Science in Optical Science and Engineering (Invited Paper)

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Abstract: University of New Mexico has developed a comprehensive plan for a new B.S. degree in Optical Science and Engineering, accompanied by teacher training and enhancement of K-12 optics education. The plan incorporates curriculum development, creation of new laboratories, development of optics courses for teachers, creation of outreach programs, and involvement of industry and government laboratories.

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1. Introduction

Over the last year, the faculty of the Department of Electrical and Computer Engineering (EECE) in the School of Engineering, the Department of Physics and Astronomy in the College of Arts and Sciences, the Department of Educational Specialties in the College of Education, and the Department of Individual, Family, and Community Education in the College of Education at the University of New Mexico (UNM) have jointly developed a comprehensive plan for a new B.S. degree in Optical Science and Engineering (OSE), with emphasis on education in the field of photonics, accompanied by teacher training and enhancement of K-12 optics education initially at the high- and middle-school levels, and eventually reaching down to the elementary school level in the implementation stage of this program. Specifically, the plan incorporates development of a new college degree curriculum, creation of new laboratories, development of courses training K-12 teachers in optical science and engineering, creation of outreach programs, identification and activation of sources of support for minority students, and involvement of local and national industry and government laboratories.

Through the incorporation of current pedagogical learning theories concerning instructional design and assessment, the new degree curriculum will support a new model that will be available for use by other engineering programs at UNM’s School of Engineering and nationwide. Most importantly, the new degree will bridge the last remaining gap in the unique hierarchy of photonics educational programs in New Mexico, starting with the Photonics Academy at West Mesa High School supported by the Sandia National Laboratories that feeds into the Photonics Technology Associate Degree program at the Albuquerque Technical Vocational Institute, and ending with the M.S. and Ph.D. programs in Optical Science and Engineering offered at UNM. The comprehensive line-up of educational and career options in optics and photonics that would be enabled by the planned B.S. degree will permit New Mexico industry to fill its photonics-centered positions at all levels, from the technician to the advanced researcher, from a workforce trained locally. The planned degree will, more generally, help meet the emerging workforce and educational needs of the entire US industry.

There is critical need for a new approach in undergraduate engineering education, and this is particularly true for a cross-disciplinary field like optical science and engineering. A major emphasis in the planning process is placed on enhancement of the quality of learning that can result from collaborative interactions between the optics and
education faculty. These are expected to create conditions in which cognitive science research will be actively conducted and applied to optics and photonics education. We further expect that this unique environment will result in the creation of the first normative model of optics and photonics professional education.

2. Rationale for developing a B.S. degree program in Optical Science and Engineering at UNM

2.1. Background

We live in a world bathed in light. We see with light, plants draw energy from light, and light is at the core of technologies from computing to surgical techniques. The field of optics concerns exploiting light to perform useful tasks.

A recent study by the Committee on Optical Science and Engineering of the National Academies of Science and Engineering entitled, “Harnessing Light, Optical Science and Engineering for the Twenty-First Century”, surveys the impending explosive growth of optics and its allied field of photonics and their unrivalled position as the next major technology to drive the economy and improve our quality of life.

The report has convincingly documented that optics is pervasive, impacting the fields of biomedicine, information technology, defense, manufacturing, energy and the environment, as well as supporting educational research activities. Light influences our lives today in new ways that we could never have imagined just a few decades ago. In the 21st century, light will play an even more significant role, enabling a revolution in worldwide fiber-optic communications, new modalities in the practice of medicine, a more effective national defense, exploration of the frontiers of science, and much more.

We are beginning to see the fruits of the scientific discoveries of the last three or four decades. The development of the laser in the 1960s produced intense light with a property never seen before on Earth: coherence. Coherent light can be directed, focused, and propagated in new ways that are impossible for incoherent light. This property of laser light has made possible fiber-optic communications, compact disks, laser surgery, and a host of other applications that add up to a multitrillion-dollar worldwide market. Applications of incoherent light abound as well, including optical lithography systems for patterning computer chips, high-resolution microscopes, adaptive optics for Earth-based astronomy, infrared sensors for everything from remote controls to night-vision equipment, and new high-efficiency lighting sources.

Although optics is pervasive in modern life, it is sometimes viewed as an orphan discipline because its power is predominantly realized in the enabling of other fields. For example, a $1B investment in photolithography gives birth to a $300B semiconductor market. Additionally, the growth of the fiber optics industry with fibers being laid continuously at the speed of a Mach 2 aircraft, about 1400 mph, empowers the information highway and fuels the burgeoning telecommunications market. Daily, in the media, we see its utility in defense, ranging from precision-guided munitions to enabling our troops to “own the night” through the use of infrared viewing devices. Traditional reconnaissance cameras are now being digitized and displayed optically. Optics and photonics are truly ubiquitous. As an ever-greater variety of commercial optical products are manufactured, the need for scientists and engineers with a broad optics education continues to rise.

While optics is essential, it typically plays a supporting role in a larger system. Central issues for this field include the following:

- How to support and strengthen a field such as optics whose value is primarily as an enabler?
- How to ensure the future vitality of a field that lacks a recognized, traditional academic or disciplinary home?

Optics and photonics promise to be as important in the future as electronics and computers have been in the past. They form one of the most important technology clusters identified by the Next Generation Economic Initiative (NGEI) for the state of New Mexico, and they greatly enhance the other clusters in biomedical, information technology, electronics and microsystems (nanoscience). New Mexico has long been a world leader in optical technologies and the industry is thriving with new and expanding companies. Photonics will support the further development of Kirtland Air Force Base in the directed energy arena (e.g. lasers, etc.) and in its growing role as the tri-service Department of Defense prime R&D center. It is worth pointing out that the NGEI initiative has amalgamated and is stimulating further growth of already burgeoning New-Mexico-based industrial and educational establishments in optics.

2.2. Existing local strengths

As indicated earlier, the proposed B.S. degree program will fill the last educational niche in optical science and engineering and respond to increasing local workforce needs for qualified technicians, engineers and scientists. It
will be greatly assisted and complemented by important resources and time-honored programs that are already in place. The most important of these unique resources are the following:

- **Photons Academy** – In the late 1990s, a new need began to emerge on the Albuquerque horizon. It revolved around Sandia’s Microsystems Initiative and the associated concern of where the technicians providing the bulk of the workforce would come from to serve this optics-enabled field. Based upon the already proven success of the Manufacturing Academy at West Mesa High School developed in the mid to late 1990s, a request for proposal was initiated by Sandia. West Mesa High School was again selected and a Photonics Academy was created, that formally articulates between West Mesa High School and ATVI. Initially, ~25 students participated in the fledgling Photonics Academy program. The 9th grade enrollment for the academic year 2002/2003 increased by 100% over the previous year, attesting to the tremendous success of the program. The most recent recruitment for the year 2003/2004 resulted in 90 applications, out of which 70 new students have been admitted to the Academy. To ensure that students coming into West Mesa are prepared for the optics academy, extensive recruiting and information sessions are held in the middle schools that feed West Mesa. Based upon its successful experience in the manufacturing area, Sandia plans to offer internships upon graduation from West Mesa High School to as many as 8-10 students/year as they continue their education. Apart from the invaluable service to the optics industry this program is likely to provide, Sandia is also in this way growing its own Microsystems staff.

The impact of this program is not limited to the vertically upward direction. To make students and parents aware of career opportunities, West Mesa High School plans to go to its feeder middle schools and introduce students to careers in optics and photonics. These informational meetings will help students “see the light” in an exciting and illuminating career in optics and photonics.

- **AAS in Photonics Technology** – This program, housed at Albuquerque Technical Vocational Institute (ATVI) and approved by the New Mexico Commission for Higher Education in August 2001, offers a one-year certificate and two-year Associate of Applied Science degree in Photonics Technology. The program has been extremely successful with bursting enrollment, and the class size had to be doubled to accommodate a strong demand among the students. The program started with 8 students in September 2001. To date, 20 students have declared they will pursue the certificate option, while 16 have chosen the AAS degree path. At present, 62 students are taking photonics-related courses at ATVI. Since this program could feed directly into the new B.S. program, its early success clearly demonstrates the need for photonics education at all levels [Navarra 2001]. It also shows that the scope and impact of the West Mesa High School Academy can be successfully broadened to include a higher-education career pathway that will open up further employment and professional development opportunities for students.

- **M.S. in Optical Science and Engineering** – A new M.S. degree program in Optical Science and Engineering, emphasizing partnership with NM Optics Industry Association (NMOIA) and the national laboratories of New Mexico, was introduced in the Fall 2002 semester. Building upon and down from the Ph.D. program in Optical Sciences, the M.S. program is designed to help meet the growing need for shorter-term specialized training in a technical area that is critical to the economy of New Mexico. This M.S. degree program was established in direct response to a strong need expressed by NMOIA. Students of this degree program will be able to pursue an Industrial Internship either at an optics industry or at a national laboratory in NM, and thus to develop first-hand appreciation for the challenges of an industrial career. The industry similarly will have a first-hand look at prospective employees and be able to train them, before they formally graduate, for a career that will serve them well. This close cooperation between UNM and the photonics industry under the M.S. program will foster a synergistic environment in which UNM can contribute to an education that has an immediate and readily measurable impact on the economy of the state and the country.

- **Ph.D. in Optical Science and Engineering** – UNM has long been a leader in graduate optics education with an interdisciplinary focus. The Ph.D. program in Optical Sciences (renamed Ph.D. in Optical Science and Engineering in Spring 2003) dates back to 1983, when the departments of Physics and Astronomy (P&A) and EECE jointly recognized a growing early need for a broad-based graduate program that covered the gamut from optical science to engineering in its overall emphasis. This program has already produced over 75 graduates who have gone on to diverse careers in industry, academia, and government laboratories statewide, nationally, and internationally. The program anticipated the need for cross-disciplinary emphasis in optics education and research that would not be widely recognized for another decade or so.

- **NSF/IGERT Program in Optics** – A Cross-disciplinary Optics Research and Education (CORE) grant involving the departments of Biology, Chemistry, Chemical Engineering, EECE, and P&A was recently funded at UNM under the NSF/IGERT program to enhance the education and training of graduate students.
The research and educational theme of the CORE project is centered on optical imaging and spectroscopic techniques with high spatial and temporal resolution and their application to physical, chemical, and biological problems. In addition to the current curricula in their respective departments, IGERT students take a set of cross-disciplinary courses designed specifically for the program. The IGERT fellows will be offered internships in the local optics industry, in national laboratories, and abroad to widen their horizons and to introduce career opportunities. A weekly seminar series will provide the students with training in technical writing and in presentations of their research in a multi-disciplinary environment. An important emphasis of the CORE program is on mentoring of undergraduate students by the CORE students, to help foster team spirit and leadership skills and to recruit, retain, and involve undergraduates, in particular those from underrepresented minorities, in research. Students enrolled in the new optics B.S. degree will be able to benefit from such mentoring.

Each of the educational initiatives described above was taken independently to solve a specific organization's need. But they have all come together beautifully, in an almost seamless manner, to create, to a large degree, a well articulated educational ladder from which students can exit and enter the workforce at different rungs, based on their needs, ability, interest, and employment opportunities. This education ladder in its entirety is unique and places New Mexico in a leading position in the nation. As illustrated in Fig. 1, the new B.S. in Optical Science and Engineering degree is the last remaining rung that needs to be added to this ladder to make it complete.

3. Improved pedagogy in undergraduate optical science and engineering

There is critical need for a new approach in undergraduate engineering education, and this is particularly true for a cross-disciplinary field like optical science and engineering. Though the basic laws of nature have not changed, there has been an extensive change in how engineers apply them to meet the needs of society, both in terms of the tools they use and the projects they work on. Likewise, there has been an enormous change in the understanding and application of pedagogy in engineering education as well as in the technology available to deliver it. It is essential that engineering education make use of the best available techniques for designing and delivering content appropriate for the 21st century.

A major emphasis in the new program will be placed on enhancement of the quality of learning that can result from collaborative interactions between the optics and education faculty. The approach towards improved pedagogy in this program will be based on a set of assumptions about human learning and educational design that is consistent with the National Research Council’s “How People Learn” framework [Bransford 1999], which takes the form of four overlapping lenses that can be used to analyze any learning situation. In particular, research on how people learn suggests that we ask about the degree to which learning environments are:

- **knowledge-centered** in the sense of being based on a careful analysis of what we want people to know and be able to do when they finish with the teaching materials or course, as well as providing learners with the foundational knowledge, skills and attitudes needed for successful transfer;

- **learner-centered** in the sense of connecting to the strengths, interests, and preconceptions of learners, and helping them learn about themselves as learners;

- **assessment-centered** in the sense of providing multiple opportunities to make students’ thinking visible so they can receive feedback and be given chances to revise their thinking in continual manner; and

- **community-centered** in the sense of providing an environment – both within and outside the classroom – where students feel safe to ask questions, learn to use technology to access resources, work collaboratively, and are helped to develop lifelong learning skills.

In order to create such a learning environment at the global level of the bachelor’s degree, we will follow a systematic instructional design process undertaken by all stakeholders that includes the discrete steps of:
• learner and task analysis;
• articulation of instructional objectives;
• description of courses based on the identified instructional objectives; and
• both formative and summative evaluation of the program design and development process.

Such a systematic design process involving all the interested parties will promote two critical outcomes: a clearer understanding of the target audience in both cultural and educational terms, and an alignment between the various constituent educational programs. We believe that such a systematic process for the development of a new degree program represents a significant departure from a typical approach taken in the past.

As discussed in more detail in Section 3.2, there is an ample body of evidence to suggest that active learning techniques leave students with a greater level of knowledge, better learning skills, and a higher rate of knowledge retention when compared with students exposed to other forms of learning. In a traditional lecture course setting, medical students’ attention was reported to be high only during the first 10 to 15 minutes and then to decline abruptly [Stuart 1978], [Penner 1984]. Hammen and Kelland concluded that very little learning occurred during lectures, when they showed only a weak correlation between lecture attendance and course grades in medical school courses [Hammen 1994]. These studies, however, focused on medical students, and to what extent they apply to other disciplines is arguable. To our best knowledge, no such studies have been reported yet in the case of optical science and engineering students. Which particular courses will benefit from active learning methods, and which courses will be more effective in their traditional setting, awaits further research. Close interactions between the optics and education faculties envisaged in the new program are expected to create conditions in which cognitive science research will be actively conducted and applied to optics and photonics education. We further expect that this unique environment will result in the creation of the first normative model of optics and photonics professional education.

On the level of individual course design, the faculty participating as designers of instruction will follow a “working backwards” strategy as articulated in *Understanding by Design* [Wiggins 1998]. This instructional design model incorporates specific strategies for achieving the research-based learning environment outlined by the National Research Council framework referenced above. *Understanding by Design* also addresses the concepts of constructivist, inquiry-based learning as a critical attribute for achieving meaningful understanding in learners as the foundation for functional competence in real world settings. As college faculty are assigned teaching responsibilities with little if any training in the systematic design of instruction, this, too, represents a significant improvement over the norm and is likely to support increased instructional effectiveness.

### 3.1. Freshman program

Throughout the USA, a dangerous trend toward shrinking engineering enrollments, noted already in the early nineties, poses a potentially serious problem for American industry and society. The annual engineering graduation rate has decreased by roughly 20% in the last decade, while the number of engineering jobs has risen by ~25-30% [Felder 1998]. The decline in the graduation rate can be attributed to both the increasing difficulty of attracting high school graduates into engineering and high attrition rates of enrolled engineering students. Most engineering schools have undertaken major recruitment efforts to address the first problem, targeting especially women and minorities. However, since freshman enrollment is heavily influenced by factors out of the university's control, these efforts have a limited potential for success [Heckel 1996]. A much more effective way to improve graduation rates is therefore to develop methods for improved retention of engineering freshmen.

Considering the strong academic records of most students who choose to go into engineering, high rates of attrition are truly alarming. A monumental study of nearly 25,000 students at over 300 institutions established that only 43% of the engineering freshmen went on to graduate in engineering [Astin 1993]. Similar results were obtained in a more limited study of 1,151 engineering freshmen at Iowa State University [Moller-Wong 1997]. After five years, 32% of the cohort graduated in engineering and 13% were still enrolled, for a probable eventual graduation rate between 40% and 45%.

With these statistics at hand, the issue of retention must lie at the heart of any new engineering program. A frequently encountered explanation of high engineering-student attrition rates is that most of those who leave lack the academic ability to cope with the rigors of the discipline. However, studies have shown that this interpretation is incorrect, with little difference in academic performance between students that choose to stay in engineering and those that choose to leave [Besterfield-Sacre 1997]. The true explanation appears to involve a complex set of factors, including students' attitudes toward engineering, their self-confidence levels, and the quality of their interactions with instructors and peers, along with their aptitude for engineering.
The present structure of freshman engineering curricula at UNM has very little engineering content, which essentially reduces the engineering degree programs to three years, with the first-year’s filter focusing on prerequisites in calculus, physics, and chemistry. We plan to utilize the positive experience of NSF-funded Engineering Education Coalitions (EECs), where even the first-year students learn engineering within a connected intellectual and social context. Significantly improved retention among students who elect to take the first-year engineering courses at the universities participating in the EECs [Felder 1998] shows that early offering of subject-oriented courses is very effective in building community and social support that are vital as students go through a challenging curriculum. This is consistent with earlier findings that students' attitudes toward engineering and their confidence levels were strongly related to their classroom experience [Astin 1993]. Compared to majors in other fields, engineering majors were much more dissatisfied with the quality of instruction they received in college and with their overall college experience. Apart from course content, the prevalent model of instruction in engineering, with its extensive reliance on lecturing and individual work and norm-referenced grading (curving), played a major role in this high dissatisfaction level and therefore in student attrition. Many educational scholars have since recommended establishing an alternative instructional environment in engineering curricula that includes the use of active and cooperative learning tools and a variety of other pedagogical methods designed to accommodate different learning styles [Astin 1993], [Meyers 1993], [McKeachie 1994].

Based on these data, we are developing an innovative first-year optical science and engineering curriculum incorporating the following pedagogical theories of the Foundation Coalition:

- Active/Collaborative Learning
- Student Teams in Engineering
- Increasing Participation of Women and Underrepresented Minorities in Engineering
- Curriculum Integration
- Continuous Improvement through Assessment, Evaluation, and Feedback
- Technology-Enabled Learning
- Curricular Change, Resistance, and Leadership

We are designing first-year courses with optics and photonics-based real-life project content, where students will be working and learning in teams. This will help them confront the difficulties they may encounter, as well as learn about the advantages of participating in a team effort. They will learn why optical scientists and engineers need to learn physics, mathematics, chemistry, ethics, economics, and social implications of technology, and they will make better connections between these subjects and the practice of engineering.

3.2. Active and cooperative learning

Research has shown consistently that traditional lecture methods, in which professors talk and students listen, dominate college and university classrooms [King 1993]. According to a study published in 1987, 89% of U.S. physics and mathematics professors lectured as a mode of instruction [Thielen’s 1987]. The greatest advantage of lectures in the opinion of teaching faculty is the ability to share information with a large number of students [Gage 1998]. However, a vast body of literature shows that students must do more than just listen to truly learn [Craik 1972], [Poppenhagen 1982], [Chickering 1987], [Bolles 1988], [Sutherland 1996]. A schematic illustration of this statement is represented in now classic “cone of experience”, shown in Fig. 2.

In active learning, students are engaged in various activities beyond just listening. They are involved in dialog, debate, writing, and problem solving, as well as higher-order thinking, e.g., analysis, synthesis, and evaluation [Bonwell 1991]. Use of these techniques in the classroom is vital because of their powerful impact upon students' learning. For example, several studies have shown that students prefer strategies promoting active learning to traditional lecture. Furthermore, some cognitive research has shown that a significant number of students have learning and cognitive styles best served by pedagogical techniques other than lecturing. On the other hand, it should be noted that the connection between student preferences and actual performance when provided with their preferred method of learning has not been well-established and requires further research [Jonassen 1993].

Classroom discussion is preferable to lectures if the objectives are to promote long-term retention of information, to motivate students toward further learning, to allow students to apply information in new settings, and to develop students' thinking and analytical skills [McKeachie 1986]. However, in order to achieve these goals faculty must be knowledgeable about alternative techniques and strategies for questioning and discussion [Hyman 1980] and must create a supportive intellectual and emotional environment that encourages students to take risks [Lowman 1984]. Hence, proper preparation of teaching faculty through workshops will be necessary. Further discussion of the need for faculty workshops and its planned implementation is presented in Section 3.6.
The published literature on alternatives to traditional classroom presentations provides a rich menu of different approaches faculty can readily add to their repertoire of instructional skills. Specific techniques that will be considered in order to incorporate active learning in the new optical science and engineering curriculum include:

- **simple modifications** of traditional lectures, for example, a faculty member allowing students to compare their notes by pausing three times for two minutes each during a lecture [Ruhl 1987], brief hands-on experiments or demonstrations in which students participate directly [Kvam 2000], lecturing by questioning (the Socratic method) [King 1993], or short, ungraded writing exercises followed by class discussion;
- **feedback lecture**, which consists of two minilectures separated by a small-group study session built around a study guide;
- **guided lecture**, in which students listen to a 20- to 30-minute presentation without taking notes, followed by their writing for five minutes what they remember and spending the remainder of the class period in small groups clarifying and elaborating the material;
- **visual-based instruction**, especially important in the context of distance education (see Section 3.5) which can also provide a helpful focal point for other interactive techniques;
- **in-class writing across the disciplines** is another productive way to involve students in doing things and thinking about the things they are doing;
- **experiential or activity-based learning** [Gage 1998];
- **problem-solving instructional strategies** which include the case study method of instruction and Guided Design;
- **interactive computer-based learning** [Burden 1998]; and
- **focused interactive learning** based on principles of dynamic social impact theory [Latane 2002].

Cooperative learning is the instructional use of small groups in which students work together to maximize their own and each other’s learning. If instituted properly, it can produce higher achievement, more positive relationships among students, and healthier psychological adjustment than do competitive or individualistic experiences. Five essential components must be present for small-group learning to be truly cooperative [Johnson 1991]:

- clear positive interdependence between students;
- face to face interaction;
- individual accountability;
- emphasis on interpersonal and small-group skills;
- processes in place for group review to improve effectiveness.

Among various cooperative learning methods, we will explore whole class and group discussions [Gage 1998], peer teaching and collaborative group learning, and role-playing or simulations [Burden 1998], as well as informal cooperative strategies such as Think-Pair Share [Johnson 1991]. In particular, we note that students working in small
groups in engineering laboratory courses were more likely to be able to generalize from specific observations, were superior at applying concepts to new situations, and had a greater ability to critically analyze what they read and synthesize information from a variety of sources [Collier 1980]. In general, students working in groups appeared to have increases in the attributes of self-directed learning and in obtaining relevant help for facilitating learning when compared with students in lecture-only courses [Poppenhagen 1982].

According to [Bonwell 1991], previous classroom initiatives and written materials about active learning have been too isolated and fragmented. The resulting pedagogical efforts have therefore lacked coherence, and the goal of interactive classrooms has remained unfulfilled. To a large extent, these statements are still true, especially when applied to UNM’s undergraduate instruction in engineering. We believe that the Bridges for Engineering Education framework adopted for the new degree program offers a unique opportunity for a coordinated efforts of optics faculty, educational researchers, and academic administrators, to make real the promise of active and cooperative learning.

3.3. Curriculum integration

The new curriculum will include elements of many disciplines, utilizing the ubiquity of optics as enabling technology in various fields, as well as its relation to the economy, manufacturing, ethics, and similar disciplines. A good example to follow has been recently set by the Department of Civil and Environmental Engineering at the United States Air Force Academy, where a capstone senior level integration course was developed [Jenkins 2002]. The course blends technical aspects of engineering design with construction and realistic issues of modern society. Technical designs accomplished by the students prior to taking the capstone course form the basis of the capstone design experience. The students review the technical design and prepare the project for construction through incorporating engineering standards and considering realistic issues, such as economics, constructability, and environmental aspects, as well as ethical, health and safety constraints. The students prepare a final design report and make an oral presentation to an interdisciplinary panel of engineering faculty. This capstone course is the culmination of a total integration experience, which includes a hands-on field engineering course, and two years of a rigorous engineering design curriculum.

3.4. Integration of research and education

The involvement of undergraduate and graduate students in research is an important and powerful educational tool. In a research setting, technical discussions between students and senior investigators, or among students, expose the student to knowledge that goes well beyond the material covered in the classroom. This allows the student to “try out” ideas that have been learnt in class and to contribute to the generation of new knowledge. In addition, the research environment provides the student with an important opportunity for professional development through interactions at conferences, meetings with program managers, and internships in government laboratories or industry. The skills of communication and networking that are learnt during these interactions are vital for today’s graduates.

The new program will benefit from the existing vibrant research in optical science and engineering conducted in both EECE and Physics & Astronomy Departments as well as in the Center for High Technology Materials, with its strong focus on photonics and sensors – areas important to homeland defense. A graduate mentorship program will be established, whereby undergraduate students will be working on research projects in a team environment, under direct supervision of graduate students. In addition, students enrolled in this program will be able to participate in UNM’s Co-op program, placing them in local industry or in national laboratories for summer internships. Both these mentorship and internship programs will greatly benefit form a similar methodology adopted for integration of graduate research, education, and training under the just begun NSF/IGERT cross-disciplinary project CORE (see Section 2.2) that stresses the role of optics in physics, biology, chemistry, and electrical engineering applications.

In addition to research experience in optics and photonic, the new program will provide research opportunities for education students who will be able to conduct research on novel teaching and assessment methods as they become implemented in this program.

3.5. Distance education

Distance education is an important instructional tool well suited to overcoming barriers of time and space. It is an effective means of facilitating learning, especially useful for reaching those unable to attend conventional university classes due to time or geographic constraints. The new program will aim at increasing the number of web-based and ITV course offerings, especially at the lower-end (first two years) of the curriculum.
Development of an undergraduate curriculum with a strong distance learning component is particularly important for the University of New Mexico with its branch campuses in Gallup, Valencia, Los Alamos, and Taos, extending as far as 150 miles away from its main campus in Albuquerque. In addition, UNM operates distance learning sites in Farmington and Zuni, as well as the two Diné College sites in Shiprock and Crownpoint. All of these sites either expect to have or already have ‘smart classrooms’ in place to teach distance education courses. Several are also hooked up to the access grid at the Albuquerque High Performance Computing Center, so that multiple sites can be rapidly reflected on the same projector screen.

3.5.1. Web-based teaching

Web-based teaching, a rapidly evolving form of technology-enabled learning, represents a tremendous opportunity for pedagogical development, and will be explored in depth for enhancing the new curriculum. The asynchronous nature of a web-course allows the student to pursue it in a convenient time setting. This flexibility empowers students, and can result in a more active and mature participation in the course.

The objective of most engineering courses is to enable each student to understand and learn a common body of knowledge. In a well-designed web-course this can be achieved by allowing different students to follow different paths to a common endpoint. This constructivist or “adaptive” approach requires more upfront time in designing the course, but the pay-off in learning gains can be significant.

Online bulletin boards provide students with another asynchronous (and therefore time flexible) forum for discussions amongst themselves and with the instructor. These interactions can foster a truly cooperative learning environment in which students answer each other’s questions and guide each other through problem areas.

With conventional learning, the student must adapt to either the classroom instructor's individual teaching style, or the predefined format of the distance-learning program. Recent demonstration at Lehigh University of the world's first web-enabled adaptive learning technology developed by Invensys PLC opens up a new avenue for courses that can accommodate individual student's learning styles to maximize teaching effectiveness. This technology can be utilized to create both face-to-face classroom programs and remote learning programs that are customized to each student's preferences. The adaptive learning technology uses a web-enabled “Learning Style Inventory”, which assesses a student's individual learning style and then adapts the specific course material. More than 80 different learning traits have been identified and are incorporated in the inventory and resulting course material created for each student. We intend to contact Invensys to explore possibilities of purchasing their technology for use at UNM.

While we believe that these new tools will allow us to significantly improve the effectiveness of our new curriculum and make the learning process more enjoyable both for students and teachers, we are aware that they are not a substitute for face-to-face learning. In the constructivist approach, the image of a teacher as a “sage on the stage” is dispensed with in favor of a learning facilitator more commonly known as a “guide on the side”. Taken too far, the constructivist paradigm can, however, become as inflexible as the instructional approach its proponents are eager to dismantle [Baines 2000].

3.6. Overcoming the barriers

An essential part of the planning process for the new undergraduate curriculum in optical science and engineering will be an identification of the obstacles to its implementation and a design of strategies to overcome these barriers.

Calls for a reform of undergraduate engineering education are not new. Yet, most teaching faculty at UNM have not bothered to seriously consider and embrace them. Part of the proposed planning process will be to conduct surveys that will help to identify and understand barriers to instructional change at UNM. These surveys will be prepared and evaluated by the College of Education participants.

Some of the existing barriers may be subjective, such as the powerful influence of educational tradition, faculty self-perceptions and self-definition of roles, the discomfort and anxiety that change creates, the limited incentives for faculty to change, and the perception of a high risk associated with the employment of active learning. There are perceived risks that students may not wish to participate, may not be able to use higher-order thinking, or learn sufficient content, that instructors will feel a loss of control, lack necessary skills, or be criticized for teaching in unorthodox ways. Other factors may be more objective, for example limited class time; a possible increase in preparation time; the potential difficulty of using active learning in large classes; and a lack of needed materials, equipment, or resources. While faculty workshops may address the subjective domain, the objective obstacles need to be clearly identified, and plans for their removal in the implementation stage will be formulated. This process is especially important since system and infrastructure upgrades would likely be required to adopt the curricular reform.

As part of our strategy towards overcoming the barriers, we intend to fully utilize the resources available through the NSF-funded Engineering Education Coalitions, focusing on faculty workshops led by invited Coalition
instructors as a way of improving the teaching effectiveness of the optics faculty. In particular, we plan to hold a series of monthly workshops on:

- Teaching Effectiveness (Student-Centered Approach to Teaching; Effective Teaching with Technology; Active/Cooperative Learning: Introduction and Applications; Active/Cooperative Learning: After the Basics; Student Teams in Engineering: Introduction and Applications);
- Curriculum Development (Freshman Engineering Programs; Interdisciplinary Freshman Engineering Design; Curriculum Integration: Why and How; Multidisciplinary Design);
- Student Success and Development (Retention of Undergraduate Students in Engineering; Bridge Programs: The STEPUP Approach; Peer Mentoring: The MAPS Approach); and
- Assessment (Planning the Assessment of Engineering Education Research; Developing Measurable Objectives and Outcomes for Programs and Courses).

These workshops will also be open to other engineering faculty, as the techniques involved are clearly of general interest and can be utilized in other engineering disciplines. Of critical importance is participation of non-engineering faculty who teach elective courses that engineering students take.

### 3.7. Outcome assessment, evaluation, and feedback

The planning process and especially the subsequent implementation of the new B.S. in Optical Science and Engineering degree will provide a fertile ground for identifying and pursuing instructional and cognitive science research problems. This will not only assist in overcoming initial barriers, but will also help to guide future practices in the classroom and to develop approaches tailored to the unique population mix of New Mexico. In particular, we envisage rigorous studies on effectiveness of active and cooperative learning strategies that will explore the impact of important student characteristics, such as their ethnic background, gender, learning styles, and stage of intellectual development. Among other factors, we plan to examine in the implementation stage the differences in performance and attitudes between students from different ethnic groups (with emphasis on Native American and Hispanic students), from different community backgrounds (rural, small town, suburban, and urban), different family backgrounds (level and type of education of parents), and between male and female students. Background information on the studied cohort will be recorded, including demographic data, SAT and AP scores, grade-point averages and grades in selected freshman and subsequent courses, and scores on both the Myers-Briggs Type Indicator® (MBTI), a personality inventory based on Jung's theory of psychological types, the Learning and Study Strategies Inventory® (LASSI), an instrument that assesses students' test-taking skills and strategies, motivation to learn, and anxiety levels, and the Motivated Strategies for Learning Questionnaire (MSLQ) derived from a program of research at the University of Michigan led by Paul Pintrich which has Motivational Scales and Learning Strategies Scales. The data will also include statistics on persistence in the optical science and engineering curriculum, and students' self-evaluations and reactions to their educational experiences. A comparison group will consist of students taking the traditional EE and P&A curricula, as well as optical science and engineering students taking traditional lecture courses. The results of this research will be disseminated in journals widely read by both education and engineering faculty.

Tom Angelo, the director of the American Association for Higher Education (AAHE) Assessment Forum, formulated the following useful definition of assessment [Angelo 1995]: *Assessment is the ongoing process aimed at understanding and improving student learning. It involves making our expectations explicit and public; setting appropriate criteria and high standards for learning quality; systematically gathering, analyzing and interpreting evidence to determine how well performance matches those expectations and standards; and then using the resulting information to document, explain, and improve performance.*

Active learning itself can be used as an effective assessment tool. Most post-secondary faculty are familiar only with summative assessment, i.e., a formal assessment in which student performance is assigned a grade that denotes a specific level of proficiency or achievement. Summative assessment typically translates into one or two major tests and a final. In recent years, however, the concept of assessment has been broadened to include formative classroom assessment, which comprises informal assessment techniques designed primarily to improve teaching and learning in a more systematic fashion [Angelo 1993]. This ungraded assessment, coupled with active learning, can be a powerful tool for transforming a passive classroom into one filled with active participants. For example, it can be used in conjunction with mini-lectures to verify whether students understand a key point or concept. Using a think-pair-share approach [Bonwell 1997] can be particularly effective to stimulate classroom discussion on a subject.

Most traditional classroom tests focus on the assessment of knowledge. Skill development has been usually perceived as something that should be done outside the classroom - in the laboratory, by solving homework problems, by writing papers, etc. Experience suggests, however, that students need explicit coaching on developing
skills inside the classroom prior to extending those skills outside the classroom. For example, to develop problem-solving skills, students can be asked to work out problems illustrative of the day's material. Such exercises allow students to develop skill proficiency in a safe environment and allow instructors to determine areas that need further explication. In this way, skill assessment can be combined with an enhanced effectiveness of instruction.

3.8. Development of new instructional materials

An important outcome of the strong interaction between the optics and education faculty and graduate students will be a series of new textbooks created in the process of development and implementation of the new program. In the past, standard textbooks have focused on a presentation of technical content accompanied by problems to be solved by students at home. Solution manuals and computer software were the only additional materials the instructors could expect to have. We envisage a novel model for creation of modern textbooks written jointly by the faculty teaching optical science and engineering courses and the experts from the College of Education who will assist in preparing unique instructional aids. These additional materials will focus on specific approaches teachers can take to introduce active/cooperative learning in their classrooms, and will contain examples of formative tests which could be used during the instruction, all in the specific context of a particular textbook. This approach will ensure the widest possible dissemination and transfer of the new knowledge acquired by the UNM faculty to other universities and colleges, and will contribute significantly to a wider use of effective teaching styles.

The new instructional aid materials will utilize the concept of abilities-based education [Bonwell 1997], with three essential components of ability: knowledge, skills, and attitudes. Evaluation criteria to be communicated to students prior to administration of the tests will also be listed. These evaluation criteria will be developed empirically in UNM classrooms using active participation by the students. Recommendations will also be included on how to train students to take part in a formative assessment of their colleagues.

4. Integrating diversity into the new program

The University of New Mexico (UNM) operates as a Carnegie Doctoral/Research University - Extensive and as a recognized Hispanic-Serving Minority Institution. The University holds a dual commitment to excellence in research and to education opportunities for minorities. It has over 30,000 students, including over 5,000 graduate students. UNM continues to strive for new levels of excellence in its teaching, research, and service, and believes that a key factor for reaching these goals lies in support for and participation from its diverse student body. UNM has a large percentage (37.5% of main campus enrollment) of minority students, especially at the undergraduate level.

According to the rankings published in the May 6, 2002 issue of Hispanic Outlook in Higher Education, UNM is ranked 15th on the list for conferring bachelor's degrees to Hispanics, 22nd for master's degrees, and 14th for Ph.D.'s. Of the 2,723 bachelor's degrees conferred in 2000, Hispanics earned 706 (25.9%); for master's, 976 degrees were conferred, 145 of them were earned by Hispanics (14.9%); for Ph.D.'s, UNM awarded 184 with 17 going to Hispanics (9.2%). On Hispanic Outlook's list of Carnegie-classified institutions by Hispanic enrollment, UNM ranks 6th in overall classification with 6,579 Hispanic students, and 1st among the Carnegie Research I institutions. The School of Engineering, ranked in 2002 as #40 in the US News and World Report Top 50 Engineering Schools in the US, attracts top quality minority students that provide a valuable pool of talent capable of conducting world-class research.

UNM benefits from diverse demographics of the state, with a 42.1% Hispanic and 8.9% Native American population base (Census 2000 data). Efforts will be made to recruit and retain in the new program high percentages of underrepresented minority students, women, and students with disabilities.

In this context, it is particularly important to include branch campuses and remote sites. For example, the lower division class at the UNM Gallup Branch is 65% Navajo and 10% Zuni Pueblo, so that 75% of the student body is Native American. Additionally, the Gallup Branch has approximately 13% Hispanic students, so that the Gallup campus is 88% minority serving. The Upper Division Teacher Education Certification & Bachelor’s Degree program graduates more Navajos than any other ethnic group. With additional outreach at the Diné College and UNM lower division programs, the Gallup Branch serves an overwhelming percentage of Native American and Hispanic students from New Mexico. These traditionally underserved populations could catalyze a solution to the employment crisis in New Mexico, especially since these same populations are very stable and have lived here for hundreds of years.

We will work closely with Diné College campuses at Crownpoint, Shiprock and Tsaile, AZ as well as the UNM Branch campuses at Gallup, Los Alamos, and Taos to serve as feeder programs to the main campus program. Cohort groups will be identified and counseled into training for the main campus program from all of these two-year, junior-college programs as well as from the lower division of the UNM main campus.
There are a large number of existing programs in New Mexico that assist students from historically underrepresented ethnic groups to prepare for and succeed in college education. For example, New Mexico MESA (Mathematics, Engineering, Science Achievement), Inc., operating on an annual budget of ~$1.6 million, prepares pre-college students for college majors and careers in mathematics, engineering, science, and related fields. During the year 2000/2001, 4,686 students were served (almost double the number of students served 10 years earlier), of which 1,667 (35.6%) were female Hispanics, 1,201 (25.6%) were male Hispanics, 273 (5.8%) were female Native Americans, and 207 (4.4%) were male Native Americans. We will be working closely with these programs to make them aware of the career opportunities in optics and photonics.

Among the mechanisms to increase the number of minority students electing to pursue the optical science and engineering degree, we envisage summer internships for high-school students from small-town and rural areas of New Mexico and for lower-division students attending UNM branch campuses. During those internships, the students will participate in various optics- and photonics-related research projects under the supervision of graduate students.

4.1. Coordination with community colleges

The new degree program requires further study in order to develop effective articulation between the Associate Degree programs at New Mexico’s community colleges and those entering with advanced placement in a baccalaureate degree program. For example, the level of math proficiency may need to be bolstered to enable the ATVI students who are articulating with UNM to move smoothly into the calculus-based science and mathematics courses required at UNM.

Programs of study in basic optics are already available at the Crowpoint Institute of Technology and Southwestern Polytechnic Institute, and would require the addition of a few classes to complete their Associates Degree level program.

4.2. Improvement of engineering content in K-12 education

UNM will work together with Sandia National Laboratories and Albuquerque Public Schools to further expand outreach programs, beyond the Photonics Academy at West Mesa High School (see Fig. 1). For example, photonics will be included in the program of Advanced Technology Academy at the Albuquerque High School. Further efforts aimed at enriching the engineering content of K-12 education will be coordinated jointly by UNM, ATVI, and Albuquerque Public Schools (APS), in collaboration with Sandia National Laboratories.

It is expected that close collaboration between the optics and education faculty will result in development of approaches that encourage current and future teachers to use stimulating problems based on optical science and engineering that illustrate real-world applications of mathematics and science. Such real-world examples are expected to increase the level of pre-college student interest and motivation, leading to an increased enrollment in engineering degree programs in general, and in the new B.S. in Optical Science and Engineering program in particular.

4.3. Teacher education

An essential part of improved engineering content in K-12 education is teacher preparation. Currently, there is a vast shortage of teachers and laboratory professional to serve the emerging needs of New Mexico’s schools and national laboratories. The new program will create new opportunities for increased interactions between engineering and education students and faculty, with the goal of enhancing the engineering and engineering technology content of the programs of study of pre-service teachers and general education majors, as well as developing new strategies for improved pedagogy and evaluation in undergraduate engineering and engineering technology.

There are presently little to no interactions between engineering and education in teacher licensure programs. An important direction that will be pursued by the participating College of Education faculty is preparation of a course for educators on the aspects of engineering in the K-12 setting.

4.4. Optics and Photonics Education Summit and a follow-on workshop

The unique optics and photonics educational environment illustrated in Fig. 1 can and should be expanded to include more K-12 schools, more community colleges, and more university campuses. We are organizing an Optics and Photonics Education Summit that will be devoted to further strengthening of optics and photonics education in New Mexico at all levels of the educational ladder (cf. Fig. 1).
In a small-and-diverse-population, large-area state such as New Mexico, collaboration, cooperation, and communication are of extreme importance to maximize the benefit from the planners and efforts of community drivers. New Mexico has selected optics and photonics to be one of its prime future economic drivers, without negative effects upon its cherished and unique character. The Summit will allow for identifying and leveraging meaningful resources, while calling attention to this emerging field. According to NSF, New Mexico ranks near, if not at the top of the nation in the ratio of R&D expenditures to gross state product – which means to many that technology for all the right reasons is more important to the well being of this state than any other. An Education Summit bringing the educational and political leaders together will help ensure and strengthen our continued technical enterprise leadership, as well as demonstrating to others our unique approach to educational requirements of an emerging-technology-based economy, especially as it applies to workforce development.

Based on the educational as well as socioeconomic issues identified at the Summit, we plan to organize a smaller, more focused follow-on workshop at UNM, concentrating on the new B.S. program. The main purpose of this workshop will be to develop actual strategies and tactics to fold in the entire range of such mostly external, often highly interdependent factors into a viable plan for the new degree program.

Our experience with the recently approved M.S. degree in Optical Science and Engineering has confirmed the efficacy of a consensus-building approach in the larger community of optics professionals throughout the State. The two-step approach we propose here, of holding a broad exploratory educational summit followed by a more dedicated and focused workshop, will not only achieve such consensus, but also lead to the development of a concrete degree proposal.

5. ABET accreditation

An important goal of the proposed program will be to achieve the accreditation status from the Accreditation Board for Engineering and Technology, Inc. (ABET). Presently, only one program related to optics has ABET accreditation, namely B.S. in Optical Engineering at the University of Alabama at Huntsville, focusing on conventional optical system design. University of Pennsylvania offers an Electronic and Photonic Materials Option as part of their accredited B.S. in Materials Science and Engineering degree program. Thus, the proposed program will be the first accredited Optical Science and Engineering degree program in the nation.

In order to assure future accreditation, all of the evaluation criteria adopted by ABET in their accreditation process will be incorporated in the proposed program.

6. Conclusions

The new program could not be more timely for New Mexico. It will bridge the last remaining gap in the unique hierarchy of photonics educational programs in New Mexico, starting with the Photonics Academy at West Mesa High School supported by Sandia National Laboratories that feeds into the Photonics Technology Associate Degree program at the Albuquerque Technical Vocational Institute, and culminating with the M.S. and Ph.D. programs in Optical Science and Engineering offered at UNM. The comprehensive line-up of educational and career options in optics and photonics that would be enabled by the new B.S. degree will permit New Mexico industry to fill its photonics-centered positions at all levels, from the technician to the advanced researcher, from a workforce trained locally. The new degree will, more generally, help meet the emerging workforce and educational needs of the entire US industry.

7. Acknowledgements

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8. References


Hands-on Demonstrations and Teaching Tools for Optics and Adaptive Optics

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Abstract: A set of demonstrations suitable for use in classrooms at the secondary, undergraduate and graduate level, and for public use in museums and science centers were developed to exhibit basic optics principles, vision science, and adaptive optics techniques. This paper will exhibit these demonstrations, and how they can be used to promote understanding of optics principles in a wide range of applicable areas. Demonstrations include units showing image formation, orientation, and scale; a unit showing 3-dimensional ray tracing through optical systems using a scattering medium and laser diodes; a unit allowing users to directly observe the color sensitivity of their eyes; and a demonstration directly demonstrating wavefront errors, image distortion, and a Shack-Hartmann sensor for wavefront measurement. Together, these bring real-world optical principles into the hands-on regime, and demystify optics principles that are difficult to visualize in three dimensions. These demonstrations are currently in use at the Keck Observatory in Hawaii, at Nauticus in Virginia, at the Yerkes Observatory and at Carthage College in Wisconsin, as well as at several middle and high schools in Illinois and Wisconsin. They have also been integrated into a unit in the Hands on Universe program published by the Lawrence Hall of Science. This work was supported by the National Science Foundation through the Center for Adaptive Optics.

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1. Overview
Optics education suffers from a lack of demonstration equipment that clearly and simply demonstrates basic optics principles. Standards such as optical rails with lenses of different characteristics, two-dimensional ray tracing models, and optics software have their place in the curriculum, but none of them completely demonstrates optical effects in a way which makes full three-dimensional phenomena clearly visible. To remedy this situation, a set of demonstrations was developed, constructed, and tested. The reader is directed to http://www2.carthage.edu:80/departments/physics/CFAO/AOIntro.htm for a detailed description of each of these systems.

2. The F-Box
Optical benches with lenses and projection screens have been used for many years to demonstrate basic image characteristics. Rather than being constrained to on-axis situations, and having only a single lens or optical train to study at a time, a setup was constructed that allows simultaneous comparison of images from several lenses (see Figure 1). The setup is referred to as an ‘F-box’, because the letter ‘F’ is used on a light box as the image source. This letter is advantageous because it possesses no symmetries; inversion or reversal is easy to detect. A board with three lenses of identical diameter (typically 5-10 cm) and disparate focal lengths (typically 50, 100, and 200 cm), cast images onto a set of projection screens, each covered with rectilinear graph papers of different line densities. It is easy for students, by careful measurement of focal length and image size, to see with this setup that the image scale is proportional to focal length; by applying masks of different aperture sizes students discover that image scale depends only on focal length, and not on aperture. Indeed, aperture stops of different sizes, shapes, and locations on each lens show that each point on the lens creates a complete image. Brightness comparisons can be made as well. It is easy to extend these experiments, and, in an astronomy setting, for example, to show how one can under- or oversample an image by using sheets of graph paper on the projection screens with cells of different sizes. Students can color-in the squares overlapping each image to see the effects of pixel size on image quality. The fastest lens in the array typically exhibits significant spherical aberration, which can be demonstrated by masking the lens into different zones and noting the best focal position for each. The lens array can also be tilted, and off-axis aberrations such as coma and astigmatism can be demonstrated. The F-box has been found to be the most useful demonstration in outreach activities, such as those conducted at Yerkes Observatory by the Hands-on-Universe program and at Nauticus in Norfolk, VA. Compact, relatively easy to construct, and very easy to operate, it makes side-by-side
comparisons of different optical effects easy to observe. A reflective version could be built, as well, though the need to offset the mirrors to throw images onto suitable screens, and the substantial cost of first-surface paraboloids, casts favor in the direction of the refractive version shown here.

![Fig. 1. The basic F-Box setup, showing the light box, lens array, and projection screens.](image)

3. Vision Box

Light is defined as that range of wavelengths (or frequencies) of electromagnetic radiation to which the eye is sensitive. The canonical image shown in a textbook on light or optics suggests that the sensitivity of the eye is described by a bell-shaped spectral distribution. However, the spectral response of the eye is actually determined by the overlapping response functions of red, blue, and green-sensitive cones in the retina. The spectral response of a real eye is more complex than that suggested by textbook cartoons. Further, each individual has a slightly different spectral response. Most extremely, those who are color blind, of course, have radically different color sensitivities from those of a color-visioned individual. Thus, it is interesting to provide users a chance to actually observe their own color sensitivity. This demonstration uses a simple slit and diffraction grating spectrograph, using inexpensive sheet-acetate grating material, to create a spectrum that is easy for a user to see. The light source is a halogen lamp; while, admittedly, a halogen lamp doesn’t provide a completely flat spectrum, its variation is far less than a simple incandescent source, and, of course, doesn’t exhibit the lines that a mercury vapor lamp shows. The apparatus has two slits, which can be used interchangeably. The first slit is of constant width, creating a light source of equal intensity along its length. A user employing this slit sees a spectrum ranging from blue to red, of constant height. The second slit has a width that becomes progressively narrower towards the top. The slit is shaped to provide a width that decreases logarithmically, rather than linearly, as this gives a better map onto the eye’s overall logarithmic response to light. On top of this slit is placed a gradient-density filter, which also various logarithmically in density with length. Together, these generate a slit source which is brightest at the bottom, and which dims with length as one proceeds towards the top. With this light spread out by the diffraction grating, the apparent height of the spectrum at each wavelength is proportional to the (logarithmic) sensitivity of the viewer. Each user therefore actually sees, effectively, a plot of his or her own color sensitivity. It isn’t possible, of course, to record this with a camera; it is the viewer who creates the viewed response. However, a camera, positioned at the viewer’s position, records an image that is itself a measure of the color sensitivity of the detector. Shown in Figure 2 is the response of a Nikon 990 digital camera. It is clear from the lower image that there are pixels that are broadly sensitive to each of red, green, and blue. It would be equally easy to measure/exhibit the response of a CCD array, or to exhibit the sensitivity of different color emulsions.
4. Ray Tracing in Three Dimensions
Optics books and those used in astronomy and vision science have diagrams that purport to show the path light rays take through optical trains. These are difficult for the novice to interpret in three dimensions. This is especially true if one is studying aberrated systems, or when the optical path is folded, both of which are common situations of interest. Optical benches are sometimes used to show light paths through systems, with screens set up in various places to sample the beam shape, but the actual light path is difficult to determine. The setup developed here lets a user view the paths of light rays through any system, walk around the system to interrogate the light path from any angle, and immediately see the changes that result from different mirrors, lenses, and positions and tilts of optical components. There are two keys to this setup: a suitable light source array, and a suitable scattering medium. The former is achieved using a ring of laser diodes (such as those manufactured for laser pointers). These must be collimated to provide a set of parallel beams. In our setups we have built rings of six diodes, and dual rings having sets of six diodes on two different diameters. The scattering medium found to work best consists of a dilution of liquid hand soap with a ratio of 1 part soap to 7 of de-ionized water providing the longest useful light path,
Figure 3. Top: Light path of a Newtonian reflecting telescope, as shown using the Ray Tracing demonstration system. Note that this is not a time exposure; the naked-eye image looks just like (actually better!) than this. Bottom: The setup used to produce the upper image. Note the primary and secondary mirrors, the ‘eyepiece’, and the laser diode array to the right.
with sufficient side scatter to make the beams easily visible. Figure 3 shows a representative example of an optical train, in this case a 4-inch Newtonian reflecting telescope, as demonstrated with this setup. It is easy to see the converging beams from the parabolic primary mirror, the turning of the beam by the diagonal mirror, and the formation of the focal plane. An additional lens can be added to be an eyepiece, rendering the light pencil parallel once again. Pictures such as Figure 3 are often created with time exposures; this one picture, however, was taken with a simple digital camera, and shows the system as it would appear to the naked eye. The eye, however, has even better dynamic range, and the system viewed by eye produces an even better, easier to see, set of rays.

This setup is also useful for demonstrating or interrogating any optical train. With a suitable tank, any collection of optics can be used, and with a suitable pattern in the diode array any geometrical aspect of the optical train can be seen. For example, it is easy to show the effects of using a paraboloid (or other conic section) off-axis; the rays no longer meet at a single point, and demonstrate coma and astigmatism. Spherical aberration can be shown using multiple, concentric rings of diodes. Using multiple elements, one could, for example, show the aberration created by an elliptical primary mirror, and she how it is corrected by a spherical convex secondary (in a Dall-Kirkham arrangement), or with a pair of hyperboloids (as in a Ritchey-Chretien).

5. The Shack-Hartmann Sensor Demonstration

One of the most exciting advances in optics is the development of adaptive systems that reduce or virtually eliminate the effects of turbulent media in the light path. This has proven especially valuable in eye and astronomy research. The heart of these systems comprises two major components: a flexible mirror that corrects wavefront errors, and, usually, a Shack-Hartmann (S-H) sensor to detect the wavefront errors. While the former is relatively easy to demonstrate (e.g., using a sheet of aluminized mylar), the latter is more difficult. In essence, a S-H sensor works by breaking a wavefront into segments, with each segment small enough to be locally flat but tilted. S-H sensors use arrays of extremely small lenses to sample each such segment, and project a set of images, one from each lens, onto a detector that, at each moment in time, notes the displaced position of each small image. Thus, the overall wavefront error as a function of position can be quantified by measuring the lateral displacement of the image created by each of the S-H lenses. It’s a fundamentally beautiful technique, but showing it in real time with an actual adaptive optics system requires not only extremely expensive equipment, but is also ineffective as one can’t actually observe the displacement of the images on the detector, which are too small and are far too rapid to see. The system shown in Figure 4 was developed to specifically demonstrate the operation of the S-H system. A light source providing a simple point of light is placed at a far distance (say, 10 meters away). The first surface mirror shown in the figure is used to fold the light path down into the demonstration, though a light source held vertically over the system would work as well, obviating the mirror. A simple plano-convex lens focuses the light from the source onto a screen at the bottom of the device. The beam is split by a beamsplitter, with one-half of the light being reflected towards a second plano-convex lens that recollimates the beam. The beam then enters an array of sixteen 2 cm diameter lenses of approximately 15 cm focal length. These project separate images onto a ground glass screen. In operation, a transparent tray of either water or, preferably, mineral oil is held over the first lens, creating slow-moving turbulence similar to that created by the atmosphere over a telescope. When moved, the tray creates enough turbulence that the image projected at the bottom of the apparatus appears totally distorted, while the individual images projected on the ground-glass screen by the lens array are near little spots, each wandering in the direction corresponding to the local wavefront tilt. A discerning user would notice that the slopes of the waves in the liquid in the tray create tilts directly correlated with the image displacements on the ground-glass screen.
Figure 4. Left: The apparatus to demonstrate a Shack-Hartmann Wavefront sensor. The upper mirror is used merely to reflect a horizontal lightpath into the system. Right: The lens array which forms the heart of the sensor. Each samples a portion of the wavefront, projecting a displaced image on the viewing screen.

6. Extensions
Among the projects currently under way is the development of a functional eye model, using the dilute soap scattering solution as a vitreous humor replacement. A flexible lens will allow one to observe the ability of the eye to focus, and the introduction of various corneal shapes can show the effects of astigmatism and long and short sightedness. With the use of additional lens elements, the application of ‘corrective lenses’ to cure visual aberrations can easily be shown. For an advanced ray tracing system, the same scattering liquid could be placed in small containers, and used as interrogators to make visible beams running through a system which is bolted to an optical bench. The S-H system could be designed around an actual telescope as the primary imager. There are many ways in which these demonstrations can be improved or modified to suit different uses and audiences.

7. Summary
The demonstrations shown here bring optical principles to light for audiences ranging from the general public in museums and science centers, to undergraduates in optics, astronomy, or biology courses covering vision. They can be used at the graduate level to make advanced optical principles clear, or in research environments where they could be used as diagnostic tools. Each is easy to construct, and is a valuable addition to the curricular tools at institutions from high schools through colleges, universities, and graduate schools. The authors would be pleased to provide additional design details, and we would be pleased to receive suggestions for improvements or ideas for other demonstrations that would make optical principles understandable.
The light fantastic: PHOTON materials for technician education

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Abstract: Project PHOTON has developed a set of instructional materials suitable for a one-
semester laboratory based introduction to photonics course. The textbook, laboratory experiment
kit and laboratory manual have been thoroughly field tested by participating high schools and two
year colleges. All materials have been aligned to national Math, Science, Technology and
Language Arts standards.

OCIS codes: (000.0000) General

1. Introduction

In August 2000, when Project PHOTON received funding from the Advanced Technology Education (ATE)
program of the National Science Foundation (NSF), only three community colleges in New England were offering
programs in photonics and high school optics labs were a rarity. The goal of the project was to increase the number
of middle schools, high schools and colleges in the six New England states teaching units or courses in
optics/photonics. Project PHOTON's strategy included

• Providing professional development for teachers to increase the number of instructors qualified to teach
optics/photonics

• Providing professional development for career and guidance counselors to enable them to speak knowledgeably
about careers in optics/photonics

• Developing alliances among educators at the middle school, high school and college levels to facilitate
articulation among levels of instruction

• Developing partnerships between educators and industry to provide school-to-career activities for students and
support for classroom learning

• Increasing student interest in optics/photonics by creating hands-on activities to supplement classroom learning

• Improving the lab facilities at participating schools through the development of a laboratory experiment kit.

Recognizing that many science and technology teachers either never studied optics or need an update on modern
applications, PHOTON featured a strong teacher professional development component. Career counselors were
included in workshops and activities to equip them with outreach information to encourage students interested in
careers in science, math, engineering and technology.

Project participants met at initial two-day workshops held in Connecticut and Massachusetts in Fall 2000. The first
day of the workshop was held at a corporate location (Zygo Corp, in Middlefield, CT and Lucent, in North Andover,
MA). At each workshop, teachers and counselors from 30 schools received an introduction to photonics technology
and listened to speakers from industry and academia discussed pathways in photonics education and careers. The
second day was for teachers only. Workshops held at college locations (Three Rivers Community College in
Connecticut and University of Massachusetts in Lowell, MA) provided teachers with take-home activities for
multiple grade levels based on the Optical Society of America (OSA) Optics Discovery Kit. The PHOTON team
described the upcoming summer workshop, the equipment kit that each school would receive, and responsibilities of
participants continuing in the project.

From the initial group of participants, 40 schools were chosen by competitive application to complete the project.
Each school team consisted of a teacher and a career counselor, and schools were required to apply as regional
alliances ideally including one college and one or more high schools and middle schools. Selected teachers attended a one-week workshop in July of 2001 held at Springfield (MA) Technical Community College. The workshop featured technical lectures and hands-on labs for teachers and a one and a half day program for counselors. Teachers worked with materials developed by the PHOTON team, including a custom designed laboratory kit. Opportunities for networking and a joint activity for teachers and counselors were included in the week's schedule. Several members of the project's industry advisory committee, as well as representatives of OSA and SPIE (the International Society for Optical Engineering) were present for all or part of the week.

During the academic year following the summer workshop, teachers worked at their own institutions to create units, courses and even entire programs in optics/photonics technology. Technical assistance was provided to participants by phone, email and personal visits from the PHOTON team. A listserv was created, allowing participants to have ready access to technical and practical curriculum advice from the project team and from each other. Industry mentors from the OSA New England Chapter volunteered to monitor the listserv and continue to take part in lively discussions of topics ranging from change of phase upon reflection from a metal to the merits and disadvantages of spending the senior year of high school in college.

In May 2002, a showcase workshop was held to allow participants to present their school's implementation of the PHOTON project. Sixteen schools made presentations, including three community colleges, 12 high schools and one middle school. Success stories included new high school labs for optics/photonics built at Tantasqua High School in Sturbridge, MA and in Bangor, ME at the United Technologies Center. Sixth graders at Tolland (CT) Middle School are exploring light and lasers in their technology education class, and new photonics courses have been developed at Central CT State University in the School of Technology.

The final PHOTON workshop was held in November 2002 to satisfy requests from teachers for an additional workshop on more advanced topics. The one-day program featured sessions in holography and optical image processing. Topics covered by demonstration and hands-on activities included creation and viewing of reflection holograms, spatial filtering, optical Fourier transforms, and using a 4f optical data processor to remove unwanted dots and lines from photographic slides.

Although the initial project plan was to create a set of notes for the teacher workshops which would be distributed to participants and to write detailed instructions for using a PHOTON developed laboratory equipment kit, the development of new materials became an important focus of the project. It was evident that suitable text and laboratory materials for teaching a complete introductory optics course at the high school/two year college level were not commercially available for participants to use in their classroom; thus a PHOTON textbook, laboratory experiment manual and teacher manual were developed. The remainder of this paper focuses on the PHOTON materials and future PHOTON development through project PHOTON2.

2. PHOTON materials

2.1 The PHOTON textbook

If high school and college students encounter optics at all, it is usually toward the end of a full-year physics course. The PHOTON textbook seeks to remedy the situation by providing an introduction to optical science and technology for students who have only a rudimentary knowledge of physics concepts. The math level is algebra/trigonometry, making the text more accessible to high school and first year college students. Practical and natural applications of optics concepts are emphasized, rather than theory and derivations. Like all the PHOTON materials, the text has been thoroughly tested in high school and community college classrooms both as a stand-alone course for non-majors and as the first course in a laser electro-optics technology program. The text has also served as the basis for one-semester online courses delivered to traditional college students, and it has been used in a corporate training environment.

As originally developed, the “set of notes” consisted of eight "modules". Using feedback from PHOTON participants and potential publishers, the work was subsequently expanded to ten chapters in a more traditional book format. The first chapter is devoted to laser safety. Although some of the optical concepts used in this chapter may not be thoroughly introduced until later in the text, the authors feel strongly that laser safety must be a first priority, even in classrooms featuring only low power Helium Neon lasers and laser pointers. Since many laboratory experiments and demonstrations in optics involve the use of lasers, it is imperative that students gain an early respect for the hazards associated with their use. It is essential that students treat all lasers with care and respect; inculcating safe behaviors at this level will help avoid accidents when students are exposed to lasers of higher power.
Subsequent chapters follow a fairly traditional exposition of optical science and technology. After an introduction to the nature of light, including an overview of radiometry and photometry concepts and units, geometric optics and wave optics are presented, followed by a full chapter introduction to optical instruments such as the camera, telescope, microscope, and several types of interferometer. The second half of the textbook includes chapters on laser physics and characteristics, laser material processing applications, and introductions to optical fiber, holography and imaging. Each chapter is richly illustrated with diagrams and photographs, many in color, to aid visual learners in understanding the material. Worked out example calculations are included to assist students in understanding the orders of magnitude relevant to the given problem. Always, practical and natural applications of optics concepts are emphasized.

To maximize usefulness of the textbook as a classroom tool, end-of-chapter conceptual questions and problems, including answers to odd numbered problems, are found in every chapter. Complete worked out solutions to the numerical problems are provided in a separate teacher manual. An appendix to the text includes a review of important concepts from mathematics and physics including scientific notation, Greek letters used in optical science and technology, right angle trigonometry, the concept of energy, and significant digits. Such information is vital when students who have not yet studied physics use the textbook in a physical science classroom.

In addition to the complete solutions to all of the chapter problems, the accompanying teachers manual contains alignment of the text materials to national science, mathematics and language arts standards for grades 9-12. This information is useful for teachers who must show that the course based on the text meets educational standards for instruction. Directions for demonstrations using inexpensive equipment are also included to assist teachers in creating stimulating presentations of optical phenomena.

2.2 Optics explorations

PHOTON participants included five middle school teachers, several of whom are now actively incorporating optics/photonics into their science or technology classrooms. In order to have hands-on activities at an appropriate level for grades 5-8, a set of six "Explorations" was created for the original PHOTON workshops. Later, the number of Explorations was increased to nine. The activities use commonly found items and OSA Optics Discovery Kit, and the language and math of the Explorations is at an appropriate level for younger students. The Explorations have been thoroughly tested by the students of PHOTON middle school participants, and include experiments such as Exploring Lasers, Exploring Diffraction and Exploring Scattering.

The Explorations may also be used as classroom demonstrations in a high school or college setting. One of the authors (JD) has created a career exploration workshop based on the PHOTON Explorations, offered each spring during a college career conference for high school students.

Fig. 1 Tolland Middle School students make lenses out of gelatin in one of the Explorations
2.3 PHOTON laboratory kit and experiment manual

The custom PHOTON laboratory kit was designed to support the experiments in basic and applied optics in the laboratory manual developed by the PHOTON project team. A list of PHOTON lab experiments and explorations is shown in Table 1. Since the summer 2001 workshop, several additional laboratory experiments have been written, and refinement to the lab materials has reclassified some of the labs as "explorations", since they require inexpensive materials and are suitable for students at the middle school level as well as high school and community college.

<table>
<thead>
<tr>
<th>EXPERIMENTS</th>
<th>EXPLORATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of Light</td>
<td>Exploring Light Spectra</td>
</tr>
<tr>
<td>Plane mirrors</td>
<td>Exploring the Pinhole Camera Viewer</td>
</tr>
<tr>
<td>Snell’s Law</td>
<td>Exploring Reflection</td>
</tr>
<tr>
<td>Single Lens: The Thin Lens Equation</td>
<td>Exploring Refraction</td>
</tr>
<tr>
<td>Systems of Two Lenses</td>
<td>Exploring Lasers</td>
</tr>
<tr>
<td>Laser Beam Collimation</td>
<td>Exploring Scattering</td>
</tr>
<tr>
<td>Spherical mirrors</td>
<td>Exploring Diffraction</td>
</tr>
<tr>
<td>Young's Double Slit</td>
<td>Exploring Polarization</td>
</tr>
<tr>
<td>Michelson Interferometer</td>
<td>Exploring Rayleigh's Criterion and Resolution</td>
</tr>
<tr>
<td>Interference in an Air Wedge</td>
<td></td>
</tr>
<tr>
<td>Diffraction Grating</td>
<td></td>
</tr>
<tr>
<td>Malus' Law</td>
<td></td>
</tr>
<tr>
<td>Brewster's Angle</td>
<td></td>
</tr>
<tr>
<td>Single Slit Diffraction</td>
<td></td>
</tr>
<tr>
<td>Laser Range Finder</td>
<td></td>
</tr>
<tr>
<td>Laser Bar Code Scanner</td>
<td></td>
</tr>
<tr>
<td>Single Beam Reflection Hologram</td>
<td></td>
</tr>
<tr>
<td>Two Beam Transmission Hologram</td>
<td></td>
</tr>
<tr>
<td>Laser Beam Profile</td>
<td></td>
</tr>
<tr>
<td>Numerical aperture of a plastic fiber</td>
<td></td>
</tr>
</tbody>
</table>

An unusual feature of the PHOTON kit is the inclusion of components and component mounts of high quality, the type one might encounter in a research lab or industry, rather than the more commonly encountered aluminum or plastic educational materials from science education supply houses. Not only is the equipment more versatile than the "educational" variety, it is similar to equipment students will see on industry field trips, making the school laboratory experience more relevant to the world of work. Because teachers are largely unfamiliar with this type of equipment, the PHOTON summer workshop devoted each of the five afternoons to learning to assemble and use the equipment.

Half of the approximately $3000 cost of each kit was paid for by the PHOTON grant and the remaining $1500 was paid by the participating institution. This matching fund requirement was a screening strategy used in the application process to establish which institutions were willing to make a financial commitment to the project. Assistance in locating matching funds was available to schools that showed a strong commitment but were unable to secure funding.

Table 2 lists the equipment and supplies in each of the kits and figure 2 is a photograph of the kit in its bright yellow packing cases. Three light sources were provided: a linearly polarized low power Helium Neon laser, a ray box/multi-feature light source, and a gas tube power supply with Hydrogen and Helium gas tubes. Each kit included a 24”x36” optical breadboard and a variety of mounting posts, post holders and base plates. The separate lens and mirror kit, plus lens mounts and flat mirrors on kinematic mounts, allowed maximum flexibility for both standard physics labs, such as investigating the thin lens equation, and for more advanced experiments, such as constructing interferometers and laser beam collimators. A small parts box contained the necessary hardware for assembly, plus small items such as a single and double slit slide and a calcite crystal.
Table 2: PHOTON Laboratory Equipment Kit

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Item Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24” x 36” Aluminum optical breadboard tapped 1/4-20 on 1” center</td>
</tr>
<tr>
<td>1</td>
<td>Ray box/Light source</td>
</tr>
<tr>
<td>1</td>
<td>Laser tilt table</td>
</tr>
<tr>
<td>1</td>
<td>HeNe laser, polarized (0.8 mWatt)</td>
</tr>
<tr>
<td>1</td>
<td>Spectrum tube power supply with one H spectrum tube and one He spectrum tube</td>
</tr>
<tr>
<td>1</td>
<td>HeNe Optical Power Meter</td>
</tr>
<tr>
<td>2</td>
<td>1 inch 50/50 Cube beam splitters</td>
</tr>
<tr>
<td>2</td>
<td>Linear polarizers, 42 mm diameter</td>
</tr>
<tr>
<td>2</td>
<td>Mounted 1” plane front surface mirror</td>
</tr>
<tr>
<td>1</td>
<td>Mounted Objective Lens f= 8 mm</td>
</tr>
<tr>
<td>1</td>
<td>Concave spherical mirror front surface f=6 mm</td>
</tr>
<tr>
<td>4</td>
<td>Plane Mirror 50 mm x 50 mm, front surface</td>
</tr>
<tr>
<td>2</td>
<td>Rotary Mount Assembly</td>
</tr>
<tr>
<td>2</td>
<td>Prism Mount Hardware</td>
</tr>
<tr>
<td>1</td>
<td>Single axis translation stage</td>
</tr>
<tr>
<td>1</td>
<td>Plate holder</td>
</tr>
<tr>
<td>6</td>
<td>Lens holders</td>
</tr>
<tr>
<td>3</td>
<td>Small base plate</td>
</tr>
<tr>
<td>2</td>
<td>Large base plate</td>
</tr>
<tr>
<td>1</td>
<td>Microscope Objective Holder</td>
</tr>
<tr>
<td>1</td>
<td>Plastic Refraction Box</td>
</tr>
<tr>
<td>4 each</td>
<td>2” Post, 3” post, 2” post holder, 3” post holder</td>
</tr>
<tr>
<td>20</td>
<td>Card mounted diffraction viewers</td>
</tr>
<tr>
<td>1</td>
<td>Flat Glass Plate kit</td>
</tr>
<tr>
<td>1</td>
<td>Quantitative Spectrometer</td>
</tr>
<tr>
<td>1</td>
<td>Iceland Spar Crystal</td>
</tr>
<tr>
<td>1</td>
<td>1 and 2 slit diffraction slide</td>
</tr>
<tr>
<td>1</td>
<td>Small Parts Kit, including 1/4-20 and 8/32 socket head screws and cap screws; hex keys</td>
</tr>
<tr>
<td>1</td>
<td>Lens and mirror kit (an assortment of 50 mm diameter lenses, flat and spherical mirrors)</td>
</tr>
</tbody>
</table>

Fig. 2 The PHOTON kit. The lens and mirror kit and breadboard are not shown.
A unique feature of the PHOTON laboratory kit and experiment manual is that each laboratory procedure was thoroughly tested using the PHOTON kit equipment to ensure that the lab experiments would actually work as intended. The authors have had the frustrating experience of purchasing equipment or lab manuals with poorly designed instructions, or worse, instructions that could not possibly work as stated. In order to avoid this situation, each experiment was first tested by the authors and by college student interns before being used by teacher participants in the summer workshop. After the workshop, suggestions for improvements made by participants were incorporated into the next version of the laboratory manual, which was then field-tested by participants’ students at their home institutions. Again, feedback from participants was used to produce an edited version of the experiments and new experiments were added on plane and spherical mirrors at participant request.

The final laboratory testing was performed by Sarah Orde, a college student intern who was a graduate of the Greater Hartford Academy of Math and Science in Hartford, CT, one of the PHOTON participant schools. While an instructor might compensate for, or not even notice, small mistakes such as a typographical error or using both upper and lower case letters for the same variable, Ms Orde was an exacting editor. As a result of her input, the lab procedures were further clarified so that, with careful reading by students, an unfavorable laboratory outcome is very unlikely.

3. PHOTON2

3.1 Adapting the PHOTON materials

The success of PHOTON in achieving its goal of increased courses and programs in optics/photonics in New England schools and colleges has led to NSF funding for PHOTON2, a national dissemination project. The PHOTON materials are now being adapted to distance learning and the resulting course will be taught online to 10-12 regional alliances nationwide. Following the PHOTON model, each alliance will include high school teachers, college faculty, career/guidance counselors and local industry.

Additional chapters on optics applications are being added to the textbook and new lab experiments have been created on numerical aperture of a plastic optical fiber and laser beam profile measurements. Additional demonstrations will be added to the teacher manual and a CD-ROM containing videotaped demonstrations of each of the laboratory exercises is being produced.

The components for the initial 40 PHOTON equipment kits were purchased from various vendors and assembled with great effort and enthusiasm by the PHOTON team, student interns and friends. For PHOTON2, LumenFlow, Caledonia, MI, has been contracted to produce the equipment kits and ship them to participants. Minor modifications have been made, for example, a smaller optical breadboard has been found to be more practical and plastic optical fiber will be included. The kit will no longer be packaged in heavy, bright yellow military surplus shipping containers, a change requested by PHOTON participants.
3.2 Adapting the Photon Professional Development Model

Project PHOTON utilized the traditional model of short (two-day and one-week) workshops, within the New England region, to train middle and high school teachers and college faculty in photonics engineering technology. The workshops provided participants with “hands-on” training in photonics curricula, use of laboratory equipment, opportunities for face-to-face interaction with peers and instructors, and exposure to career opportunities. Workshops were supplemented with technical assistance and on-going communication (e.g., phone, email, listserv, and in-person visits) to ensure a high level of support and a continuous learning experience. While the PHOTON project provided an effective model for teacher and faculty professional development on a regional basis, this highly concentrated learning experience had some shortcomings. First, it compressed a great deal of new information into a short timeframe and did not allow the participants sufficient time to reflect and absorb content material. Second, the follow-up to the short-term workshop model required a great deal of technical assistance and on-going communications.

To overcome the limitations of the traditional short-term professional development model and to effectively disseminate the highly successful field-tested PHOTON instructional materials and alliance model nationally, PHOTON2 will employ a web-based distance learning approach supported by the infusion of “adult learning principles” to provide learners with a collaborative, inclusive, and sustained learning environment through the use of modern technology.

3.3 Utilizing Distance Learning To Disseminate Nationally

With the advent of the World Wide Web, the use of the Internet for delivery of educational materials, instruction and training has revolutionized higher education. Advantages of web-based courses include the ability for learners to learn at their own pace, access information at a time and place that is convenient to the learner, and communicate easily with instructors and peers (Quintana, 1996). Researchers argue that in contrast to face-to-face instruction, online courses provide learners with extended reflection time through asynchronous dialogue allowing learners to compose thoughtful, probing contributions (Collison, Elbaum, Haavind, & Tinker, 2000). Web-based instruction allows individuals from around the corner and around the world to come together to form a close-knit community of collaborative learners that capitalizes on professional and common interests.

The format and structure of the PHOTON2 web-course will use collaborative or group learning principles and strategies to facilitate professional development among teachers and faculty. In collaborative learning, instruction is learner-centered rather than teacher-centered and knowledge is viewed as a social construct, facilitated by peer interaction, evaluation, and cooperation (Hiltz, 1998). Fundamentally different from traditional teacher-led instruction, collaborative learning employs instructional methods that encourage learners to work together on academic tasks and construct knowledge and ideas through interactions and responses from others. In collaborative learning, the role of the instructor changes from lecturing to transfer of knowledge to facilitating learner’s construction of his or her own knowledge. Research shows that collaborative learning results in more learner involvement with the course, more engagement in the learning process, and is more effective than traditional methods in promoting learning and achievement (Hiltz, 1994; Harasim, 1990; Johnson, 1981). Experts from a number of different fields and from remote geographic locations can “log on” to a threaded discussion on a specific topic and provide insight and fodder for thought that adds richness to the learning experience that would otherwise not be possible. Web-based courses also offer learners instant access to vast amounts of resource material available through the Internet for comparison and research within a dialog. To fully access the benefits available through web-based learning, PHOTON2 will assist teachers and faculty in developing proficiency as web-based learners.

3.4 Incorporating Adult Learning Principles

While web-based instruction has many positive aspects, it also has some downsides. These include high dropout rates among learners; a feeling of isolation in the learning process; and a lack of personal connection to instructors and fellow students. Furthermore, instructors who are unfamiliar with the educational framework and support structures necessary for successful self-directed learning may develop web-based versions of traditional curriculum by simply “cutting and pasting” course material into the web-based environment. PHOTON2 will address these issues by designing and developing web-courses from the ground up in collaboration with experts in adult learning to establish a pedagogical foundation of guided inquiry whereby learners construct their own knowledge in the context of a supportive and collaborative learning environment. PHOTON2 Co-PI Dr. Marijke Kehrhahn from the Neag School of Education at the University of Connecticut (UConn), a nationally recognized leader in adult learning methodologies, will oversee the pedagogical aspects of the web-based course development. The project will also
draw from the expertise of other nationally recognized experts in the field of adult learning and distance education including Dr. Barry Sheckley and Dr. Alexandra Bell from UConn and Dr. Morris Keeton from the University of Maryland University College (UMUC). PHOTON2 will also draw upon the research of the Concord Consortium, an NSF-supported organization involved in the development of effective facilitation of web-based instruction.

The development of the PHOTON2 web-course will be guided by three principles of effective adult learning adapted from Keeton, Sheckley, and Griggs (2002):

Principle 1: Active Learning. Learning that is active results in the development of learner proficiency. Instruction must include hands-on experience, reflection, practice, and feedback to actively engage learners in constructing and organizing a rich knowledge base that they can successfully apply to real problems of practice.

Principle 2: Continuous Learning. Learning that is continuous results in the development of proficiency. Instruction must include sufficient number of contact hours over a span of time to enhance learner processing and problem solving.

Principle 3: Coherent Learning. Learning that is linked to genuine problems of practice results in the development of proficiency. Instruction must be centered around the problems of teaching and program development that faculty face to allow for practice with employing new knowledge in real world contexts.

By integrating strategies that engage learners through active, continuous, and coherent learning within the context of web-based instruction, PHOTON2 will create a collaborative learning environment and experience that will allow learners to: (1) develop the self-directed learning skills necessary to support life-long learning; (2) apply and adapt the content knowledge and learning strategies learned in their own courses and institution; and (3) establish and maintain a collaborative learning community consisting of students, educators, and industry professionals that supports the transfer of learning through synergistic learning activities.

Finally, in addition to providing web-based professional development to teachers and faculty on a national level, PHOTON2 will contribute to the growing body of research on web-based learning. Numerous studies have been conducted to determine the effectiveness of distance education as compared to traditional classroom instruction. (Russell, 1999). While researchers generally report positive results with respect to learning outcomes, they also argue that more research is needed to identify factors related to learning outcomes specifically in the context of web-based instruction (Phipps & Merisotis, 1999). To address this gap, the PHOTON2 team of researchers will conduct comprehensive quantitative and qualitative analyses throughout the duration of the project to determine the extent to learner characteristics and learning environment, as well as situational and institutional factors relate to learning outcomes and transfer of training. Ongoing formative evaluation and feedback will ensure that teacher and faculty needs are addressed during the course and that the opportunity for learning is maximized. Research results will culminate in peer-reviewed journal publications and a comprehensive guide for effective web-based instructional delivery and facilitation for teacher and faculty professional development.

4. Conclusion

Project PHOTON developed curriculum materials for a one semester course in optics/photonics that can be used at the high school or college level, including a draft textbook, laboratory manual, teacher manual and laboratory equipment kit. Using a traditional model of professional development, 40 teachers throughout New England were trained in the use of the materials, and guidance and career counselors were made aware of career opportunities in the field. The materials have been thoroughly tested by PHOTON schools, many of whom now have photonics courses or programs as a result of PHOTON participation.

The PHOTON materials will be further refined and expanded as a result of PHOTON2, a national dissemination project beginning in July 2003. A new model for professional development for teachers and counselors in optics/photonics will also be developed, using distance learning and incorporating adult learning strategies. It is expected that additional courses and programs will be created in schools and colleges nationwide as a result of PHOTON2.

5. References


6. Acknowledgements

PHOTON: A Curriculum Development, Teacher Enhancement and Laboratory Development Project

Funded in-part by the Advanced Technological Education program of the National Science Foundation.(ATE #ATE 0053284) Principal Investigator, Judith Donnelly, Three Rivers Community College; Co-Principal Investigators Fenna Hanes (Project Manager), New England Board of Higher Education; John Swienton, Exfo USA, Inc.; Senior Personnel Nicholas Massa and Barbara Washburn, both Springfield Technical Community College

PHOTON2: Web-based Collaborative Learning for Teachers

Funded in-part by the Advanced Technological Education program of the National Science Foundation.(ATE #ATE 0302528) Principal Investigator, Fenna Hanes (Project Manager), New England Board of Higher Education; Co-Principle Investigators, Judith Donnelly, Three Rivers Community College; . Marijke Kehrhahn, Neag School of Education (University of Connecticut); Nicholas Massa and Barbara Washburn, both Springfield Technical Community College
OptoSci Educator Kits – an Immediate Solution to Photonics Teaching Laboratories

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Abstract: The burgeoning growth of the worldwide photonics and optical communications industry has imposed ever increasing demands on the supply of suitably skilled engineers and scientists who can design, install and operate modern photonics systems. In recognition of this need OptoSci, in collaboration with university academics, has commercially developed a series of hardware based teaching packages in optics, optoelectronics and optical communications. Each educator kit is fully self-contained, including all of the optoelectronic hardware and comprehensive literature support. This saves the academic tutor considerable development time and enables the kits to be immediately installed in the photonics teaching laboratory to support accompanying lecture courses. A fundamental design objective of our educator kits is to provide students with hands-on practical experience of photonics components, instruments and systems and allow them to investigate essential physical principles and key technical issues relevant to their lecture courses. This paper will outline the design philosophy behind the products to meet the desired educational aims, and then examine the specific educational objectives and topics investigated in each educator kit.

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OCIS codes: (000.2060) Education; (060.2330) Fiber optics communications; (060.4510) Optical communications; (230.7390) Waveguides, planar; (260.0260) Physical optics; (140.3510) Lasers, fiber; (060.2320) Fiber optics amplifiers and oscillators; (060.2410) Fibers, erbium

1. Introduction

Photonics technology currently drives major technical advancement in a wide diversity of technologies such as telecommunications, measurement science, industrial and environmental sensing, medical diagnostics and biosciences. In particular, the world’s main trunk telecommunications systems, the global internet and mobile phone communications systems are all founded on Photonics networks. Companies operating in these fields have an ever increasing demand for highly skilled scientists and engineers who can design, build, analyse, install and operate photonics systems. There is no doubt that the learning experience of these professional technologists is greatly enhanced during their graduate or undergraduate studies by exposure to hands on, practical experience of photonics components and systems. OptoSci Ltd, in collaboration with academics at Strathclyde and Heriot-Watt Universities, has developed a suite of Photonics Educator Kits which enable students to experimentally investigate all of the major technical features, principles and design issues of optical waveguides, optical communications systems, optical networks and OTDR, erbium doped fibre amplifiers and lasers. These application oriented kits are also supported by a range of experiments examining the fundamentals of physical optics, covering reflection, refraction, polarisation, diffraction, coherence and interference. In the development of all of these systems we adhere to a strict design philosophy and procedure, which ensures that all of the important educational objectives are met.

2. Design Philosophy

The overall educational aims of the experimental exercises are to enable students to consolidate their understanding and knowledge of photonics as presented in an accompanying lecture course and to acquire practical experience of the design, analysis and characteristics of photonics components and systems. To achieve these aims it is essential to take a fully integrated approach to the design of laboratory based photonics teaching packages including the design of dedicated hardware, experimental procedures, exercises and manuals. To ensure that all desirable educational objectives are met and that all of the most important scientific and technical principles, issues and
phenomena are addressed, we have developed our suite of fully integrated laboratory based teaching packages in accordance with the following design rules:

- Define the educational objectives in terms of the physical principles, important technical features, design issues and performance characteristics which must be addressed, with particular attention to facilitating student understanding and ability to implement concepts.
- Define the experiments to meet these performance objectives.
- Design the dedicated (custom) hardware to enable the proposed experimental investigation whilst keeping costs within realistic academic teaching budgets.
- Formulate the experimental procedure and manuals to guide the students through the investigation and results analysis (in some cases more open ended investigations may be formulated with minimal guidance to the students).
- Formulate tutorial exercises and case studies to relate the results to real world devices and systems.

The primary constraint is cost and the final packages must be affordable within higher education budgets. In general, the packages have been designed as far as possible to be self-contained so that as little ancillary equipment as possible is required. However, where it is advantageous and cost effective to use equipment normally available in student laboratories, the packages have been designed to be compatible with the capabilities of such equipment e.g. a 20MHz or 50MHz oscilloscopes.

3. Photonics Educator Kits

Using the design principles referred to above, OptoSci has commercially developed a unique range of fully self-contained laboratory based teaching packages for use in universities, colleges, and industrial training centres. The current series of educator kits allow students to perform detailed experimental investigations of the following topics:

- Optical Waveguiding
- Fibre Optic Communications
- Erbium Doped Fibre Amplifiers
- Physical Optics
- Optical Network Analysis - OTDR
- Lasers

The kits are designed in conjunction with senior academics from the internationally renowned optoelectronics teaching and research groups at Strathclyde and Heriot-Watt Universities to ensure high quality products that are directly relevant to teaching or training courses in this technological field. Furthermore, each package is a fully self-contained unit, incorporating all of the components and optoelectronic instruments required to perform the experiments thus allowing each kit to be immediately installed in the teaching laboratory. In addition, each educator kit is supplied with extensive literature support for the tutor and student. This includes, student manuals which describe the relevant background theory and experimental procedures; instructor’s manual with sample results for all
experiments and exercises; detailed lecture notes with case studies and design exercises, and a series of tutorial
questions with solutions.

The table below summarises some of the features and benefits of this range of teaching packages

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully self contained package</td>
<td>⊆ Saves 2 to 3 years of course, literature and hardware development</td>
</tr>
<tr>
<td>Competitively priced</td>
<td>⊆ Available for a price which is realistic within academic budgets</td>
</tr>
<tr>
<td>All specialised experimental hardware is supplied</td>
<td>⊆ Allows immediate installation in the laboratory</td>
</tr>
<tr>
<td>Comprehensive laboratory literature support</td>
<td>⊆ Full background and experimental support for tutor and student</td>
</tr>
<tr>
<td>Full lecture notes and tutorials provided</td>
<td>⊆ Provides extensive background material for lecture course</td>
</tr>
<tr>
<td>Designed in conjunction with leading academics</td>
<td>⊆ Totally relevant to photonics courses in academia</td>
</tr>
<tr>
<td>Easily tailor experimental programme for different student levels</td>
<td>⊆ Suitable for all undergraduate and masters level photonics courses in Physics and Electronic Engineering</td>
</tr>
<tr>
<td>Straightforward to reconfigure for open ended projects</td>
<td>⊆ Can also be used for project based experiments</td>
</tr>
<tr>
<td>Innovative design philosophy</td>
<td>⊆ Ensures that all desired educational objectives are realised and that students investigate all major technical issues</td>
</tr>
<tr>
<td>Hundreds of kits are currently used in leading academic institutions world-wide and we experience continued repeat business</td>
<td>⊆ Positive endorsement of the educational value of the products by both tutors and students</td>
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<tr>
<td>Full product support is available</td>
<td>⊆ Just contact us by e-mail, phone, or fax</td>
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*Table 1: Features & Benefits of OptoSci’s Photonics Educator Kits*

Based on the many benefits that our range of photonics educator kits offer and the very positive feedback we have obtained from students and lecturers alike, we believe that these innovative products offer the tutor an immediate and cost effective solution to the provision of comprehensive and stimulating experimental courses in key areas of optics, optoelectronics, and optical communications.

The following sections provide a summary of the key educational objectives for each of the teaching packages and then briefly describe the associated experimental programme used to achieve these aims. A more detailed description of some of the background theory, experimental hardware, results and analysis is provided in previous publications [1-3] and on the OptoSci website [4].

4. Optical Waveguiding

Information transmission along an optical fibre is governed by the principles and characteristics of optical waveguiding. The simplest approach to introducing students to the concepts and properties of optical waveguides is to begin with the principles of total internal reflection and then address the ray model of firstly step index, and then graded index planar waveguides. To support lecture courses on these topics, the overall objectives of the Optical Waveguiding package are to enable students to experimentally investigate and consolidate their understanding and knowledge of:
• the principles of refraction, reflection and total internal reflection.
• the principles of optical waveguiding using the ray model and the concept of guided modes.
• the principles and practice of the prism coupling technique for the measurement of modal parameters and the investigation of mode spectra, and as an illustration of phase matching.
• elementary waveguide analytical techniques.
• basic waveguide design processes including concepts of mode cut-off and the design of single mode waveguides.

Figure 2: Optical waveguiding educator kit

To meet the educational objectives stated above the students carry out the following investigation:

• Measurement of Snell’s law.
• Measurement of the Fresnel relationships for both polarisation states with observations of Brewster’s angle, the critical angle and total internal reflection (comparisons are carried out with theory).
• Establishment of prism coupling to selective waveguide modes and observation of output coupled mode lines (m line spectra).
• Measurement of mode coupling angles and mode effective indices / propagation constants for
  - Step and graded index planar waveguides.
  - Both polarisation states.
• Determination of the waveguide parameters (index profiles and thickness) from the mode effective indices.
• Calculation of mode cut-off conditions using the waveguide parameters.
• Design and test of single mode waveguides.

5. Fibre Optic Communications

Optical fibre information transmission links enable more information to be transmitted over greater distance than any other communications technology. Hence, they have all but completely replaced copper based systems as the primary choice for global and local telecommunications systems. The objectives of the Optical Communications experiments are to enable students to experimentally investigate and build upon their knowledge and conceptual understanding of, and their ability to interpret:

• The main characteristics of the major components of a fibre optic communications system i.e. the source / transmitter, the fibre channel (attenuation, dispersion, pulse spreading etc.) and the receiver
• The overall system performance limitations imposed by the component characteristics
  - the maximum possible link length limited by attenuation
  - the bit rate (and bandwidth) / length products determined by fibre dispersion
• System design and performance analysis.
To achieve these objectives the students carry out the following investigations:

Stage 1. Power Budgets
- Measurement of the power / current characteristics, bias points and launched powers of the laser and LED transmitters.
- Measurement of connector losses.
- Measurement of the fibre attenuation coefficient.
- Measurement of the receiver noise and sensitivity.
- Calculation and comparison of the attenuation limited link lengths for the laser and LED transmitters.

Stage 2. Temporal Characteristics
- Measurement of the step function response of the transmitter / receiver, the system and the fibre using both the laser and the LED. This enables the determination of
  - the fibre impulse response for both the laser and the LED
  - the modal and material dispersion coefficients
  - the bit rate distance products for both the laser and LED transmitters.
- Measurement of the analogue signal frequency response of the transmitter / receiver, the system and the fibre, leading to determination of
  - the analogue bandwidth and bandwidth distance products of the fibre for both the LED and laser sources. It is interesting to compare the directly measured bandwidth with that obtained from the step response
- Measurement of the impulse response with direct determination of the fibre dispersion coefficients.

Stage 3. System Performance and Analysis
- The design of systems to meet a given specification using the measured data.
- Analysis of the performance of systems to determine if they will meet a required specification.
- Design and performance analysis for state of the art systems at 1.3 & 1.55 µm to compare with the results for the system investigated.

6. Erbium Doped Fibre Amplifiers And Lasers

Direct optical amplification using erbium doped fibre amplifiers (EDFAs) is now preferred over optoelectronic repeaters as the primary means of restoring the signal power in long distance fibre optic links and branched networks. In addition, lasers (essentially optical oscillators) are simply optical amplifiers with positive feedback, again highlighting the importance of optical amplifiers in modern photonics systems. The objectives of the EDF optical amplifier and laser experiments are to enable students to investigate and become practically familiar with the principles and characteristics of optical amplifiers and lasers in general, and erbium doped fibre amplifiers and lasers in particular. To achieve these objectives the EDF amplifier and laser experiments enable:
- Measurement and analysis of small and large signal gain as a function of pump power
- Measurement of gain as a function of signal power and pump power
Investigation of gain saturation and determination of point of transparency, gain gradient and gain efficiency

Determination of saturated output power as a function of pump power

Investigation of amplified spontaneous emission (ASE) and ASE-ASE and Signal-ASE beat noise. This includes a study of their dependencies on pump and signal power

Determination of output signal to noise ratio and Noise Figure for the EDFA

Construction of an EDF laser

Examination of single pass amplifier gain characteristics

Investigation of the laser output power characteristic (threshold and slope efficiency) as a function of the output coupling ratio and the intra-cavity loss.

Figure 4: Erbium doped fibre amplifier educator kit

7. Optical Network Analysis - OTDR

In optical fibre networks, signal losses occur in the fibre itself, at splices and connectors and in the excess loss mechanisms within components like couplers and wavelength division multiplexers. With the passage of time, faults, such as fibre breaks, may occur, and splices, connectors and components degrade, resulting in increasing transmission losses which jeopardise the system performance. Optical time domain reflectometry (OTDR) is the industry standard technique employed for measuring the loss characteristics of a fibre link or network, monitoring the network status and locating faults and degrading components. Hence the main objectives of the network analysis laboratory exercises are the investigation and practical familiarisation with:

- Network configurations
  - point to point, branched and WDM networks
- The principles and characteristics of network components
  - connectors, splices, couplers and WDMs
- The use of an optical time domain reflectometer (OTDR) including trace acquisition and manipulation
- OTDR trace analysis, feature identification and component / fibre loss assessment
- Fault identification and location.
The students carry out the following investigation in four stages to build up skills and knowledge towards the analysis of complex networks:

Stage 1. OTDR trace acquisition and analysis for point to point links at both 1.3\(\mu\)m and 1.55\(\mu\)m
- OTDR operation and functions
  - trace acquisition, cursor controls and zoom functions
- Identification of trace features and loss events: dead zones, Fresnel reflections, loss events and ghost reflections
- Measurement of distances and losses at events (splices, connectors, faults etc.)
- Measurement of the fibre attenuation coefficient and its wavelength sensitivity (1.3\(\mu\)m & 1.55\(\mu\)m).
- Measurement of bend losses and their wavelength sensitivity (1.3\(\mu\)m & 1.55\(\mu\)m).

Stage 2. Branched networks with fibre couplers - Coupler loss analysis
- Measurement and interpretation of losses across a fused fibre coupler event.
- Estimation of the coupler insertion and excess losses from the OTDR trace loss measurements (given knowledge of the coupling ratio, \(K\)).
- Estimation of the coupling ratio, \(K\), from the loss measurements.
- Determination of the wavelength sensitivity of \(K\) (1.3\(\mu\)m & 1.55\(\mu\)m).

Stage 3. WDM networks with multiple fibre coupler branches
- Trace acquisition and investigation of the 1.3\(\mu\)m & 1.55\(\mu\)m branches of a WDM network.
- Measurement of WDM insertion loss and isolation.
- Detailed investigation of the 1.55\(\mu\)m branch beyond the WDM with analysis of coupler losses.

Stage 4. Fault location and identification on networks with deliberately introduced faults
- Identification of line faults and determination of their losses.
- Identification and loss analysis of faults at couplers and WDMs - coupler degradation or splice degradation and its location.
- Identification, location (distance and which branch?) and loss analysis of line faults in particular branches of a multi branch network.

8. Physical Optics

The Principles of Physical Optics educator kit addresses the fundamental properties of light and the principles of physical optics. It consists of four individual modules covering detailed experiments in polarisation, reflection and refraction, diffraction, interference and coherence. The objective of this suite of modules is to provide the grounding in some of the basic properties of light, which are then applied in some of the kits described previously.

The students carry out the following experiments

8.1 Polarisation
- Confirmation of Malus’s law.
• Investigation of the properties of half and quarter wave plates (alignment, axes identification, polarisation characteristics).
• Measurement of the state of polarisation of a light wave.
• Investigation of quarter and arbitrary waveplates (Stokes parameters, the polarisation ellipse and the Poincaré sphere).
• Examination of strain birefringence and its application to strain sensing.

8.2 Reflection And Refraction
• Reflection and refraction characteristics at an internal and external optical interface for both s- and p-polarisation states.
• Confirmation of Snell’s Law at low to high index and high to low index optical interfaces.
• Confirmation of the Fresnel Equations
• Identification of features such as Brewster’s Angle and the critical angle for total internal reflection.
• Determination of the refractive index of an optical element.

8.3 Diffraction
• Investigation of near and far field diffraction patterns for apertures and slits of various dimensions (Fraunhofer and Fresnel diffraction).
• Confirmation of the width of various known slits and apertures and determination of the width of unknown slits and apertures.
• Experimental investigation of diffraction at a reflective grating, including the basic grating equation (confirmation of grating line density).
• Multiple order diffraction, the Littrow configuration, grating resolution and resolving power as a function of incidence angle and diffraction order using two wavelengths.
• Determination of the wavelength of a second laser.
• Diffraction through a transmission grating and measurement of line spacing.

8.4 Interference And Coherence
• Construction of a Michelson interferometer and investigation of its multiple and single fringe alignment configurations.
• Assessment of the surface quality of three different optical elements inserted into one arm of the interferometer.
• Calculation of the wedge angle for one of the elements.
• Investigation of the coherence function of a Fabry-Perot cavity laser.
• Examination of the coherence length of the Fabry-Perot cavity laser as the laser’s drive current is varied.
• Determination of the coherence length of the laser and measurement of its cavity length.
9. Conclusions

A suite of laboratory based experimental teaching packages has been developed for modern optics, photonics and optical communications courses. OptoSci’s innovative design philosophy ensures: that all of the desired educational objectives are realised; that all major technical issues are addressed; and that each complete package can be offered for a price which is realistic within academic budgets. The kits are suitable for both physics and engineering based courses since they address fundamental physical principles, key technical issues, component and system performance characteristics and design processes (many of which, such as dispersion in optical fibres, were hitherto precluded by cost from the teaching environment). Furthermore, since each educator kit is fully self-contained the tutor is provided with all of the experimental equipment and literature support to immediately establish a teaching laboratory in key areas of photonics technology, in addition to providing extensive teaching material for the associated lecture course. Ultimately then, the key benefit for the tutor is that each of these unique and comprehensive teaching packages saves two to three years of course, literature and hardware development effort.

10. References

4. Extensive additional information on OptoSci’s range of photonics educator kits (i.e. full data sheets, a sample student manual, detailed educator kit specifications, and journal publications on the products) is available in the “Product Support” section of our website www.optosci.com.