

## **2006-1496: THE LASER CULT: HANDS-ON LABORATORY IN PHOTONICS**

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Alan Cheville is an associate professor of electrical engineering at Oklahoma State University. Starting out along the traditional tenure path as a researcher in THz ultrafast opto-electronic devices, his interests are shifting to the larger problem of engineering education. Dr. Cheville is currently engaged in several curriculum reform efforts based on making engineering more relevant to students and emphasizing student development to an equal degree as content.

# The LASER CULT: Hands-on Laboratory in Photonics

## Introduction: Challenges in Teaching Optics

The unique nature of the field of optics creates challenges for effectively teaching optics in engineering disciplines. *Harnessing Light*, a study by the National Academy of Sciences<sup>1</sup>, points out that “Although optics is pervasive in modern life, its role is that of a technological enabler: It is essential, but typically it plays a supporting role in a larger system.” To enable the teaching of optics in science and engineering program the study identifies two issues that need to be addressed when designing programs that teach optics: “How to *support and strengthen* a field such as optics whose value is primarily enabling” and “How to *ensure the future vitality* of a field that lacks a recognized academic or disciplinary home.” It is an open question how to effectively teach optics as a (usually small) subset of an engineering or physics curriculum.

For many years, the School of Electrical and Computer Engineering at Oklahoma State University (ECEN) taught a lecture-format course in optics. Based on student comments and ABET assessment data, the traditional, lecture-based teaching approach did not adequately the two issues identified in *Harnessing Light*. In the traditional approach, faculty designed optics courses to give students an understanding of fundamental principles; lecture was supported by and structured around the optics textbook. While students gained an understanding of optical principles, students were not able to use optical techniques in engineering practice. Faculty in ECEN concluded that *supporting and strengthening* optics requires that engineering students both understand the principles of optics and be able to apply these principles to their discipline. *Ensuring optic’s future vitality* requires that the one to two optics electives a typical engineering student will take enhance that student’s chance of and choice for optics-related employment and encourage students to pursue graduate studies in optics.

To better teach the importance and applications of optics in the electrical engineering program and overcome some of the limitations inherent to lecture, ECEN created a two course sequence in photonics: the Light Applications in Science and Engineering Research Collaborative Undergraduate Laboratory for Teaching (LASER CULT). LASER CULT courses are designed to make optics relevant to engineering students, and allow students to apply optics concepts to a practical engineering design problem. Since most students have little foundational knowledge in optics, courses explicitly teach why optics is relevant to electrical engineering and how to apply knowledge of optics to a relevant engineering problem.

## Structure of LASER CULT Courses

The LASER CULT emphasizes relevance to students by scaffolding knowledge on case studies and replacing lecture with active learning. Active learning incorporates formative evaluation in which assignments are aimed at different levels of Bloom’s Taxonomy to address student development. Bloom’s Taxonomy identifies levels of knowledge and helps faculty identify students who have mastered those levels. Multiple pedagogical techniques are used that address learning at different levels on Bloom’s taxonomy: 1) independent reading with formative evaluation helps individual students master fundamentals (remember and understand), 2) follow-up active learning in class helps student teams apply knowledge to a design problem (apply and

analyze), and 3) design projects have students test how useful acquired knowledge is (evaluate and create). The following paragraphs describe, in chronological sequence, the structure of LASER CULT courses. The sequence is shown below in figure 1. Following the description of the course structure the design projects used are discussed, followed by assessment data on student learning.

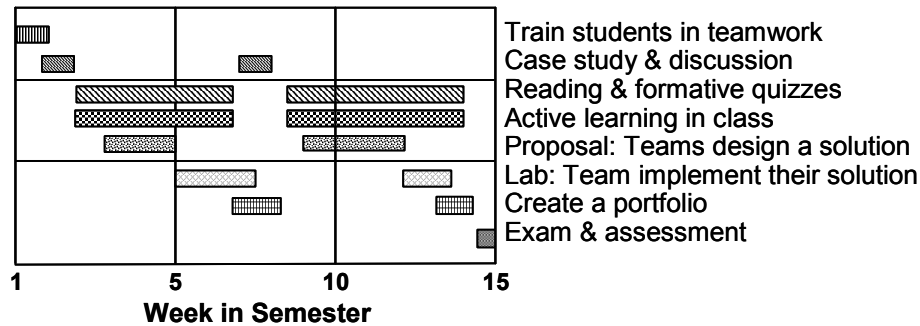


Figure 1: Organization of different pedagogical elements in one semester course.

LASER CULT courses purposely limit the range of topics covered to enable students to pursue an optics design project in depth, helping them develop the evaluate and create levels of learning. Each course introduces two design projects that student teams design and build from individual components. Design projects are done on teams, and the first week of the semester is devoted to team building exercises. Teams are heterogeneous<sup>2</sup> and contain three to five students.

All learning in the LASER CULT is done in the context of the project. Each project is introduced with a case study<sup>3</sup> that makes the material relevant, enables all students to begin the class with the same preconceptions, and links knowledge from electrical engineering to optics. The case study incorporates emerging knowledge with ethical and social issues as a story in a context relevant to students, often a problem encountered by young engineers at a small start-up company. In each case study the protagonists are presented with a design problem, which student teams will solve later in the course. Since students have little or no prior knowledge of the design problem being covered, the case study includes introductory concepts with citations. Since students construct new knowledge by building upon prior knowledge, class discussion of the case study helps to identify new concepts or those which are not fully understood. The case study provides a framework, or scaffold, that links individual concepts together; class discussion of the case study creates common preconceptions, providing a context for learning.

Over the next four to six weeks students individually cover a series of reading assignments from the textbook, web sites, or interactive JAVA applets outside of class. For each day class meets, an on-line reading assignment is given that contains a formative quiz to test student understanding. These quizzes, given in the WebCT course management system, are simple problems designed to highlight important concepts in the reading assignment and written to focus on the two lowest levels of Bloom's Taxonomy: *remember and understand*. Typical questions involve defining what technical terms mean, using "plug and chug" formulas, or identifying MKS units for various quantities. Each quiz can be taken multiple times, and students are provided immediate feedback on their performance. These quizzes are worth 15% of the course grade.

When student teams arrive in the classroom, they are given a set of more difficult problems that apply concepts from the reading to the project. These problems are written in the context of the case study, and show students how to apply concepts from their reading assignment to the design problem first introduced in the case study. Typical active learning exercises contain two to four problems and integrate concepts from the most recent reading assignment with previous readings. The problems are graded, and all students on the team are given the same score; these exercises count for 15% of the course grade. The difficulty and content of these problems is chosen to address the apply and analyze levels of Bloom's Taxonomy. During the class period the instructor move throughout the classroom, informally meeting with teams to clarify conceptual misunderstandings. Unlike traditional courses where such problems are given as homework assignments, any problem in which students may develop misconceptions are done in class where the instructor can immediately respond. Some of these in-class assignments require teams to take measurements in the laboratory to familiarize them with equipment used in building or characterizing the project.

While student teams are learning concepts and how they can be applied in the classroom, the teams begin to design a solution to the problem posed in the case study. After approximately three to four weeks of studying concepts, teams submit a design proposal that contains analytical and/or numerical models showing they have a potential solution to the problem posed. The proposal must reference existing work as well as outline specific responsibilities of each team member on a Gantt chart. This proposal does not count towards the grade, rather teams are allowed to begin to build their project only after their design proposal, evaluated using a rubric, has a score of 90% or higher. The instructor evaluates all proposals and provides feedback to teams on deficiencies or flaws in their design. The proposal also contains a budget through which teams choose all the components and instrumentation needed to construct the project. Components are chosen from an on-line catalog developed for LASER CULT courses<sup>8</sup> and are listed at retail prices from vendors to familiarize the students with the actual cost of their design. Teams only have access to items they request in their budget.

After the team's proposal is accepted, a teaching assistant assigns the team space on a bare optical table, and checks out all the parts requested by the team. The team then proceeds to build their design and test whether it functions. Students self-schedule laboratory hours, freeing up faculty time and reducing the number of required teaching assistants. Constructing a project is a type of problem based learning<sup>4</sup>. Usually a follow-up to the case study (progressive disclosure) is done at this time to make sure all teams understand the design problem. One potential difficulty inherent to problem based learning is task overload in which students (novices) spend excessive time on problems that are easily solved by a TA or faculty (experts). The fact that students self-schedule time in the lab contributes to task overload, but requiring a rigorous design proposal help eliminate some of these problems as does working out many of the design issues in the problems given in class. To further minimize waste of student time, each team is credited 10% of the project budget to spend on consulting. Faculty and TA's charge consulting fees to aid teams in design or construction. Although seemingly time consuming for faculty, this has proven to be an extremely effective method to help minimize the faculty time used in teaching a design intensive course. By associating time with money, students come prepared with questions

and only seek instructor input as a last resort.

Project construction addresses, to some extent, the upper levels (synthesis and evaluation) of Bloom's Taxonomy by permitting students to test the validity of their conceptual understanding. Additionally, the project makes the design experience relevant and authentic; experimental design work is by nature a complex problem that serves to reinforce the value of cross-disciplinary knowledge. In order for a team to successfully complete the design project, they must draw on skills beyond those specifically addressed in class. Students must also develop effective teamwork skills since projects are too complicated for most individuals.

The project concludes with a written report submitted by the team. To emphasize the importance of communication this report is the only part of the project that is graded; each project is worth 25% of the course grade (50% total). The report is graded using a rubric, and teams may submit the report before the deadline to obtain feedback from the instructor. While the exact format of the report varies between projects, all reports contain measured specifications and individual statements by each team member. Having student teams generate project specifications is key to addressing the upper levels of Bloom's Taxonomy. Generally student teams have great difficulty generating meaningful specifications. On the day that the final report is due, teams demonstrate their projects during class, showing the project meets the reported specifications.

At the time the report is due, students are also required to complete a peer evaluation and a student assessment of learning gains (SALG)<sup>5</sup>. The peer evaluation is formalized using a web reporting system developed for this project that enables each team member to evaluate the overall contributions of the other team members and for each team member to view how they were rated by others. An individual student's project grade is scaled by the mean rating given by their team members<sup>6</sup>, and any team member who receives a peer rating of less than 70% on both projects fails the course. Fewer than 3% of students fail the course due to peer evaluations; properly selecting teams and training students to function on teams helps avoid problems with peer ratings. Peer evaluation has proven to be highly effective in helping equalize contributions from all team members<sup>6</sup>.

The course ends with a final examination given in two parts. The first part consists of questions from the formative quizzes given to reinforce important concepts. The second part is a pencil-and-paper design problem that determines whether students can individually apply the concepts learned in class. The two exams are worth a total of 20% of the course grade. In the LASER CULT grades are not curved or weighted by the instructor. Students are, however, allowed to adjust the relative contribution of quizzes, in-class exercises, project reports, and the final exam by  $\pm 5\%$ .

### **LASER CULT Course Content**

The two LASER CULT courses are a junior level introduction to optics/photonics and a senior level course on lasers. There are two design projects in each course<sup>7</sup>. The projects in the junior course cover geometrical optics and imaging, and a project on optical spectroscopy. Projects in the senior course cover laser beam propagation and construction of a laser. The four design projects used in these two courses are described below.

The geometrical optics project has student teams design and build a zoom lens during which the students play the role of an engineering design team at a small company. Zoom lenses are optical devices capable of changing magnification with little shift of the image plane. Typically both the magnification change and complexity of the system increase as more lenses are used, introducing engineering design trade-offs. In the design phase, student teams first describe their system using polynomial equations to demonstrate their design serves as a zoom lens, then model the system and the effects of aberrations on image quality using commercial ray tracing software. Student teams build their lenses using commercial cage or rail systems. Images are acquired on a CCD camera and saved as electronic files. Imaging targets, including grid and line patterns, allow team to measure the lens modulation transfer function and grids of colored LED lights are used to measure chromatic aberration.

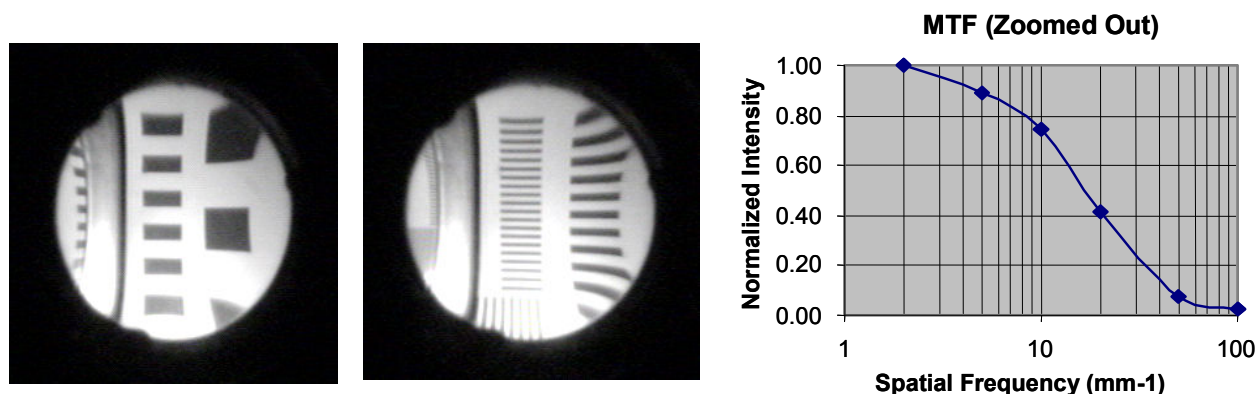


Figure 2: Data taken by a student team from zoom lens (left) used to measure modulation transfer function (MTF) of their zoom lens (right). The MTF of an optical system is used to characterize the level of detail an optical system can measure.

Several case studies are used in the spectroscopy project which has student teams design, build, and characterize a fluorometer. The most popular case study is a forensic investigation of blood stains at a crime scene in which student teams track down a serial killer. This design project covers the concepts behind, and interactions between, components of a fluorometer—light sources, detectors, filters, and phase sensitive detection—as well as fundamentals of spectroscopy and emphasizes how photonics interfaces with electrical engineering. Teams design a fluorometer to minimize detection of excitation wavelengths while maximizing throughput of the target fluorescence.

The senior course, which covers operation of lasers also incorporates two design projects. The first is the design of optical tweezers. The case study introduces this technique as a way to manipulate individual DNA bases. Optical tweezer design requires in-depth understanding of Gaussian beam optics and propagation, and the design proposal requires that teams design an optical system to focus a HeNe laser beam to a minimum spot size with a 100× microscope objective by matching the beam profile and radius of curvature to DIN or JIS standards. For safety, low power HeNe lasers are used for alignment, then a 15-20 mW HeNe laser is used to trap 3.7  $\mu\text{m}$  latex spheres. This is an extremely popular project. Teams have trapped pond

organisms, e-coli bacteria, and made patterns of spheres by moving them to the surface of the microscope cover slip.

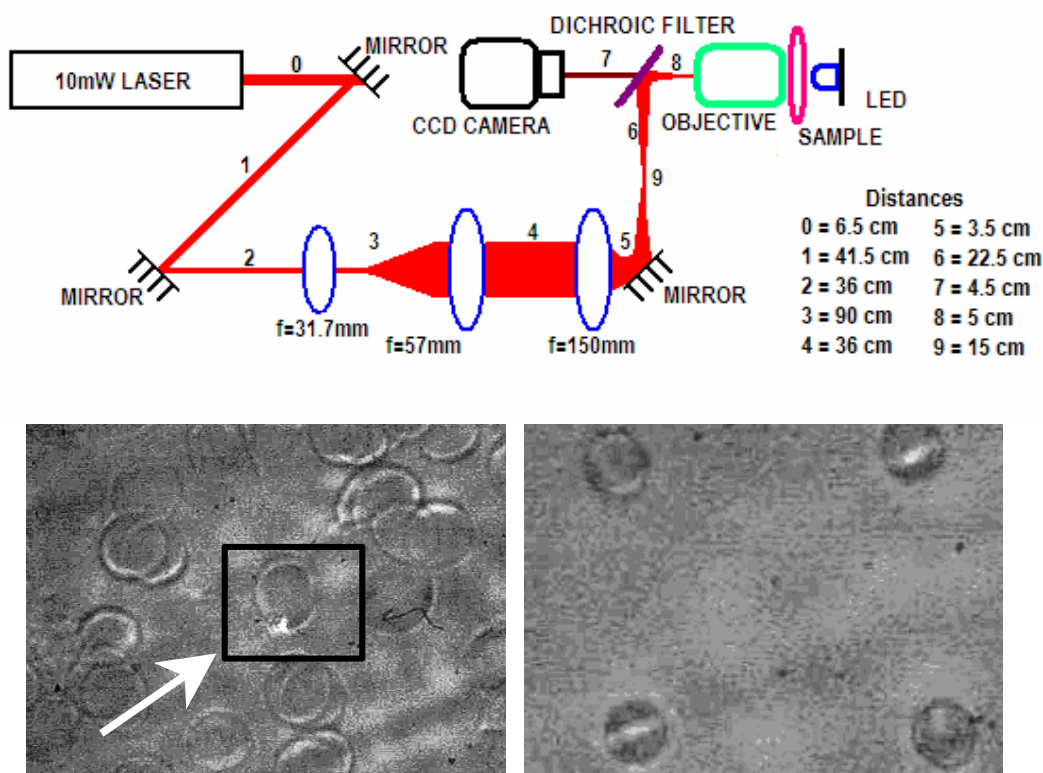


Figure 3: The top figure is the schematic diagram of the optical tweezers built by a student team. The lower figures are trapping of human red blood cells (left), and a square pattern of  $3.7\ \mu\text{m}$  particles made using optical tweezers (right).

The final design project is designing and building a frequency doubled, diode-pumped solid state laser using neodymium doped vanadate ( $\text{Nd:YVO}_4$ ) as a gain medium and the nonlinear material KTP for second harmonic generation. In the design phase, teams design a stable laser cavity and model laser gain media with coupled differential rate equations incorporating the Einstein coefficients. Due to the difficulty of this project, the requirements for the design proposal are more stringent. As part of the work done in-class, teams measure the fluorescence lifetime and spectrum of  $\text{Nd:YVO}_4$  and the wavelength vs. temperature dependence of the diode laser pump to acquire data used in the design proposal. For this project students receive extensive safety training. This project is unforgiving of poor design choices. While nearly all teams achieve lasing, there is a wide range of power outputs which depend on mode matching the pump and cavity beams and the beam size within the KTP crystal.

### LASER CULT Evaluation

As discussed previously, the primary outcomes of the LASER CULT are to *support and strengthen optics* by teaching how and why optics is relevant to electrical engineering and

*ensure optic's future vitality* by encouraging students to pursue graduate studies. The course format of the LASER CULT is extremely effective in making optics relevant to students and stimulating interest in graduate school. Assessment data was collected for the LASER CULT courses from 2001 to 2005. The assessment tools used are a Student Assessment of Learning Gains (SALG), student generated portfolios containing individual reflective statements by each student<sup>8</sup>, and statistical data from the formative quizzes. The statistical data from formative quizzes is used primarily to improve formative evaluation and the level of in-class assignments rather than to measure summative changes in student learning.

The Student Assessment of Learning Gains is used to analyze student perceptions of team function, the case study, the design projects, written reports, and peer evaluations. SALG results were compared with one page reflective statements from each student given in the project reports. A qualitative review of personal statements and SALG responses was performed to assess student attitudes and learning gains for the educational goals of the LASER CULT.

Relevance was a significantly repeated theme in student statements; 94% of students reported that the scaffolding provided by the case study made the problem more relevant. Students also reported that having to chose parts, design then build their project, and measure performance helped learning; 78% reported it made the material more relevant and promoted learning. Comments from students often indicated that they saw applicability of the projects to their future careers. Such comments were often tied closely to positive statements about teamwork.

The emphasis on teamwork also helps students master concepts; 94% of students report they learned more by working on a team than individually. Since both courses are electives, the sample population could potentially be self-selected towards those students who favor a group-oriented approach. Students made repeated references in individual statements to the benefits of a cooperative, team-based approach to problem solving. Themes common to the positive responses were division of responsibility, patience with others, cooperation, and the necessity of a well defined team structure as opposed to the amorphous groups often formed by students. Negative student comments were most common for unfair distribution of effort and language barriers.

The environment of the LASER CULT is designed to mimic that of industrial or academic research program with the commensurate emphasis on depth of understanding rather covering a broad set of concepts. The SALG asked students if emphasizing a single project affected the amount or quality of student learning; only 20% of students indicated that the focus on two projects rather than more numerous homework assignments negatively affected how much they could have learned. On average, 85% of the students indicated that they learned more in LASER CULT courses than they would have in a lecture course. The SALG results show that students feel that graded activities make the largest contributions to their learning. It was intended to use pre/post final exam scores to better quantify changes in student learning, but changes to the course made this impossible.

Students were informed by the instructor at multiple points in the course that the LASER CULT's emphasis on in-depth projects was designed to mimic a graduate research program. The senior level laser course SALG asked students how their experiences in the course impacted how



likely they were to attend graduate school. The responses were given on a Likert scale with 1 representing much less likely (negative impact) and 5 being much more likely (positive impact). The responses had a mean score of 4.12; no students reported the course had a negative impact, 38% reported no impact, and 62% reported a positive impact. In comparison, a control sample of three junior level courses taught using lecture had a mean score of 3.07 with a negative impact on 7% of students, no impact on 79%, and a positive impact on 14% of students.

In conclusion, the LASER CULT integrates different active learning methods to separately address student learning on different levels of Bloom's Taxonomy. The course format addresses some of the issues outlined in the National Academy report *Harnessing Light*<sup>1</sup> that are needed to support and grow optics and photonics. Assessment data indicates the LASER CULT makes course concepts more relevant to students and provides positive experiences in functioning on a team through a focus on in-depth projects. The LASER CULT is synergistic with ABET outcomes, particularly "soft" outcomes (d, g, h, and i of criterion 3).

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