Annual Report for Period: 06/2007 - 05/2008

Submitted on: 05/27/2008

Principal Investigator: Stroud, Carlos R.

Award ID: 0633621

Organization: University of Rochester

Title:

CCLI-Phase I: Quantum Optics Laboratory for the Undergraduate Curriculum - Teaching Quantum Mechanics with Photon Counting Instrumentation

Project Participants

Senior Personnel

Name: Stroud, Carlos

Worked for more than 160 Hours: Yes

Contribution to Project:

Carlos Stroud is the project Principal Investigator. He is one of the main persons involved in the project. He selected students for the project and supervised their research on building the teaching experiments. He negotiated with the Vice-President and the Dean of Monroe Community College the involvement of this College in the project.

Name: Mooney, William

Worked for more than 160 Hours: No

Contribution to Project:

Prof. W. Mooney retired because of his wife's illness. We met with Vice-President and Dean of Monroe Community College to transfer MCC involvement in the project to other activity.

Name: Lukishova, Svetlana

Worked for more than 160 Hours: Yes

Contribution to Project:

Svetlana Lukishova is a co-Principal Investigator of the project. She is one of the main persons who constructed teaching instruments and supervised the students in building these instruments. She developed teaching strategy and wrote the manuals.

Name: Knox, Wayne

Worked for more than 160 Hours: Yes

Contribution to Project:

Wayne Knox is a co-Principal Investigator of the project. He lead the efforts on the educational impact of both the new instrument and its modules for undergraduate students. He included the overview of four prepared teaching experiments in his lecture course 'Optics in the Information Age'.

Post-doc

Graduate Student

Name: Bissell, Luke

Worked for more than 160 Hours: Yes

Contribution to Project:

Luke Bissell developed a confocal microscope used in two teaching experiments. He supervised undergraduate student participating in the development of teaching experiments.

Undergraduate Student

Name: Zimmerman, Brandon

Worked for more than 160 Hours: Yes

Contribution to Project:

Brandon Zimmerman participated in a development of the project of entanglements and Bell's inequality lab. He also participated in a development of the project on confocal fluorescence microscope imaging of semiconductor colloidal quantum dots and spectral measurements.

Technician, Programmer

Name: McIntyre, Brian

Worked for more than 160 Hours: Yes

Contribution to Project:

Brian McIntyre is a hardware and software engineer. He also helped to develop a website.

Other Participant

Name: Adamson, Per

Worked for more than 160 Hours: Yes

Contribution to Project:

Per Adamson participated as an internal evaluator of this project.

Research Experience for Undergraduates

Organizational Partners

Monroe Community College

We invited Monroe Community College (MCC) Vice President Janet Glocker and Dean Dianna Phillips to visit the Institute of Optics for discussion about our collaboration. Director of University of Rochester Center on Entrepreneurship D. Moore also participated in this meeting.

After discussion of training of optical technicians at MCC we decided that the optimal form of our collaboration will be
(1) participation of University of Rochester team in the Science Day organized by MCC for Finger Lake area two-year colleges and high-schools;
(2) demonstration of quantum optical experiments with photon counting instrumentation to MCC students;
(3) participation of MCC professors in a workshop organized by the Institute of Optics.

Other Collaborators or Contacts

We contacted Corning Community College. Prof. Thomas A. Dunbar visited the Institute of Optics on our invitation. We discussed transferring our single-photon interference experiments to two-year college student program. Prof. Dunbar described the modern optics experiments which he established in Corning CC.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

SEE ATTACHED FILE FOR MORE DETAILS ABOUT RESEARCH AND EDUCATION ACTIVITES

During the first year period of funding, our MAIN RESEARCH AND EDUCATION ACTIVITIES have been focused on following challenges:

äh Developing and building four teaching experiments at the Institute of Optics, University of Rochester (S. Lukishova, C. Stroud, students L. Bissell and B. Zimmerman):
- entanglement and Bell's inequalities;
- single-photon source interference in Young's double-slit and Mach-Zehnder interferometers;
- confocal fluorescence microscopy of single-emitter fluorescence;
- Hanbury Brown and Twiss setup and fluorescence antibunching.

äh Developing the manuals for these teaching experiments;

äh Preparation and teaching the course on Quantum Optics and Quantum Information Laboratory (S. Lukishova) to six students from three departments;

äh Meeting with Monroe Community College Vice President Janet Glocker and Dean Dianna Phillips regarding collaborative activities;

äh Meeting with Corning Community College Professor T.A. Dunbar, discussion of his teaching experiments on modern optics and his involvement in our projects.

äh Demonstration of four quantum optics experiments to near 26 students of the course 'Optics in the Information Age' (S. Lukishova, W. Knox);

äh Demonstration of four quantum optics experiments to group of students of Colgate University visiting the Institute of Optics with their Prof. E. Galvez (We adapt and implement his experience on building and teaching photon quantum mechanics experiments);

äh Evaluation of students' knowledge by questionnaires, report and essay writing, and oral presentations;

äh Dissemination of results by writing papers and conference paper submissions;

äh Organizing future workshop-symposium 'Quantum Optics and Quantum Engineering for Undergraduates' during the Annual Meeting of the Optical Society of America (Rochester, NY, October 23, 2008). We invited 5 speakers ('Undergraduate Quantum Optics: The Challenge and the Excitement', M. Fox, Univ. of Sheffield, UK; 'A Quantum Optics Laboratory for Teaching Quantum Mechanics', E. J. Galvez, Colgate Univ; 'How to Write a Successful Educational Proposal to the NSF', W. W. Hein (NSF); 'Teaching Quantum Mechanics with Photon Counting Instrumentation', C. R. Stroud. G. Lukishova, Univ. of Rochester; 'The Challenges of Quantum Physics as Pedagogical Tools, A. G. Zajonc, Amherst College) and announced contributed oral and poster paper submission. After the symposium, all participants will be transported to the University of Rochester for a demonstration of the Quantum Optics and Quantum Information Teaching Laboratory at the Institute of Optics.

äh Website preparation;

äh Dissemination of results by demonstration of teaching experiments to Prof. E. Galvez (Colgate University) and professors from University of Arizona (H. Gibbs), Arizona State University (C-Z. Ning), University of Maryland, Baltimore County (T. Pittman).

äh Students' research on room-temperature quantum-dot-doped liquid-crystal photonic-bandgap samples' development for efficiency increase of a single photon source (S. Lukishova).

äh Sharing the new equipment with other research groups, for instance, (i) single-photon EM-CCD-camera has been used in students' research of R. Boyd's and J. Howell's groups on quantum optics; (ii) time-correlated single-photon-counting PC-card was used separately in the Laboratory for Laser Energetics, University of Rochester, both by students of R. Sobolewski in research on NbN receivers and in A. Schmid's nanometrology group;

äh Evaluation of the first step of the project by the internal evaluator;

äh In addition to current room (210 sq. feet), recently the Institute of Optics provided two rooms for the course labs (175.4 sq. feet and 242 sq. feet).

äh Spectra-Physics donated a 250-mW UV argon ion laser with etalon inside for entanglement and Bell's inequality lab.

Findings:

SEE ATTACHED FILE FOR MORE DETAILS REGARDING MAJOR FINDINGS

Here are the highlights of these findings:

CONTRIBUTION TO KNOWLEDGE BASE OUTCOME:

äh Four teaching experiments were built at the Institute of Optics, University of Rochester (S. Lukishova, C. Stroud, students L. Bissell and B. Zimmerman):

- entanglement and Bell's inequalities;
- single-photon source interference in Young's double-slit and Mach-Zehnder interferometers;

- confocal fluorescence microscopy of single-emitter fluorescence;
- Hanbury Brown and Twiss setup and fluorescence antibunching.

äh Manuals were written for four experiments with photon counting instrumentation.

äh Students participated in this project co-authored one paper submitted to refereed journal, one conference proceeding and two submitted conference abstracts.

äh Minority student Brandon Zimmerman participated in three national undergraduate symposia with oral presentations.

äh We submitted a paper to the workshop during the Summer meeting of the AAPT, describing our teaching experiments.

LEARNING OUTCOME:

äh More than forty students benefited from these teaching experiments. Among them are students of three departments of the University of Rochester as well as students from Colgate University.

äh Using questionnaire with 36 questions on photon quantum mechanics showed that one half from participated students answered correctly more than 75% of questions, 70% of students answered correctly more than 70% of questions and all students answered correctly more than 60% of questions.

äh Students' mastery in photon-counting instrumentation is shown in that 50% of students received total scores of 'A' and the rest of students received total scores of 'A-'. The grades were based on students' capability of carrying out the experiments, writing the reports and delivering oral presentations.

COMMUNITY BUILDING OUTCOME:

äh We interacted with investigators working on similar or related approaches: Prof. E. Galvez (Colgate University), Prof. M. Beck (Whitman College), Prof. A. Zajonc (Amherst College), Prof. M. Fox (University of Sheffield, UK).

äh Teaching experiments were shown to Prof. Gibbs (University of Arizona), Prof. T. Pittman (University of Maryland Baltimore County) and other visitors of the Institute of Optics.

äh A Workshop-symposium 'Quantum Optics and Quantum Engineering for Undergraduates' was included in the program of the Annual Meeting of the Optical Society of America (Frontiers in Optics)/Laser Science Conference (Rochester NY, October 23, 2008).

äh Prof. Stroud delivered lectures on public colloquium at the Case Western Reserve University entitled 'Visualization and control of atomic electrons' and for general public at the Laboratory for Laser Energetics S&T seminar entitled 'The history of optics at the University of Rochester'.

Training and Development:

SEE ALSO ATTACHED FILE

Training of six students from three departments of the University of Rochester was accomplished during the first year of the project (Fall semester). These students were enrolled in the course 'Quantum Optics and Quantum Information Laboratory' (Lukishova). All students carried out four teaching experiments, wrote reports and essay, delivered oral presentations and answered questionnaires. They worked six hours per week during 15 weeks in groups of two or three students. Two teaching assistants of the course were also trained on these equipment (Detailed description of the experiments is presented in previous section).

One student from this course (Brandon Zimmerman) continued to work on the project selecting it as his research project. He delivered talks at three national undergraduate symposia as well as at the Conference of the National Society of Black Engineers (students' chapter). Four students of the course were selected as co-authors in refereed publications (one journal submission and one published conference proceeding).

In addition, some 26 students of the Institute of Optics enrolled in the course 'Optics in the Information Age' (Knox) participated in a lecture-demonstration of these laboratory experiments. This demonstration provided students a laboratory experience with the concepts that they studied on the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.) Approximately ten students of Colgate University and five high-school students participated in similar demonstration.

Some equipment of Lab. 3, EM-CCD camera is practically in use almost every day in the students' research both of PI and co-PI groups and by students of other groups. For example, in our collaborative research with Prof. Boyd (Department of Optics) and S.-H. Chen (Department of Chemistry) on dye-doped cholesteric liquid crystal laser this camera was used by students to record the spatial distribution at the output of cholesteric laser with a high dynamic range.

Faculty of different Universities visited Quantum Optics and Quantum Information teaching experiment facility learning the experience of the Institute of Optics. Among them were Prof. Gibbs (University of Arizona), Prof. T. Pittman (University of Maryland Baltimore County), and Prof. E. Galvez (Colgate University), Prof. T. Dunbar (Corning Community College).

Outreach Activities:

1. Prof. Stroud delivered a lecture for general public at the Laboratory for Laser Energetics S&T seminar entitled 'The history of optics at the University of Rochester' (October 2007).

2. Prof. Stroud delivered a lecture on Public Colloquium at the Case Western Reserve University entitled 'Visualization and control of atomic electrons' (April 9, 2008).

3. Undergraduate minority student Brandon Zimmerman delivered four lectures about the role of adiabatical following in classical and quantum mechanics and single-photon detection using single-emitter fluorescence at the following conferences:
  - Annual McNair Undergraduate Research Conference (University of Maryland, Baltimore County, Fall 2007);
  - National Society of Black Engineers, Annual Fall Regional Research Conference (Fall 2007);
  - National Conference for Undergraduate Research (Maryland, Spring 2008);
  - National Undergraduate Students in Technical Research Competition (Orlando, Florida, Spring 2008).

4.Graduate student Luke Bissell participated in optical experiment outreach activity with high-school students (Spring 2008).

Journal Publications

S.G. Lukishova, L.J. Bissell, V.M. Menon, N. Valappil, M.A. Hahn, C.M. Evans, B. Zimmerman, T.D. Krauss, C.R. Stroud, Jr., R.W. Boyd, "Organic photonic bandgap microcavities doped with semiconductor nanocrystals for room-temperature single photon sources on demand", Journal of Modern Optics, p. , vol. , (2008). Submitted,

S.G. Lukishova, L.J. Bissell, C.M. Evans, M. Hahn, Y.J. Choi, C.J. Clarkson, X.F. Qian, T.D. Krauss, C.R. Stroud, Jr., R.W. Boyd, "Visible and telecom-wavelength single quantum dots in 1-D photonic bandgap chiral microcavities", Proceedings of the Quantum Electronics and Laser Science Conference, CLEO/QELS 2008, Optical Society of America, May 4-9, San Jose, CA, p. paper QFA, vol. , (2008). Accepted,

Books or Other One-time Publications

C.R. Stroud, S.G. Lukishova, "Teaching quantum mechanics with photon counting instrumentation", (2008). Invited presentation, Invited
Editor(s): Optical Society of America, Frontiers in Optics/Laser Science Conference
Collection: Symposium-workshop "Quantum Optics and Quantum Engineering for Undergraduates" (Oct. 23, 2008)
Bibliography: Technical Digest

S.G. Lukishova and C.R.Stroud, Jr., "Quantum optics and quantum information teaching laboratory", (2008). Presentation on the workshop, Submitted
Editor(s): American Association of Physics Teachers
Collection: Workshop "Photon Quantum Mechanical Labs" of AAPT 2008 Summer Meeting
Bibliography: Technical Digest, Post Deadline

C.R. Stroud and S.G. Lukishova, "CCLI - Phase I: quantum optics laboratory for the undergraduate curriculum - teaching quantum mechanics

with photon counting instrumentation
", (2008). Poster presentation, Accepted
Editor(s): National Science Foundation
Collection: CCLI PI Conference, Washington D.C., August 13-15 (2008)
Bibliography: Poster presentation

S.G. Lukishova, C.R. Stroud, Jr., L.J. Bissell, B. Zimmerman, "Teaching experiments on photon quantum mechanics", (2008). Poster presentation, Submitted
Editor(s): Optical Society of America
Collection: Frontiers in Optics/Laser Science Conference (October 19-23, 2008, Rochester NY)
Bibliography: Technical Digest

Web/Internet Site

Other Specific Products

Product Type:

Instruments or equipment developed

Product Description:

With participation of undergraduate students we developed single-photon device instrument for future use in quantum communication. Two teaching experiments are developed using this instrument.

Sharing Information:

Some modules of this instruments are in use by other groups of our University, e.g. Prof. Boyd and Prof. Howell's students used our EM-CCD camera for their quantum optics experiments, Prof. Sobolewski's students used our time-correlated single-photon counting PC board TimeHarp 200 for measurements of characteristics of his superconducting detectors.

Product Type:

Teaching aids

Product Description:

Our students prepared videos of fluorescence of single quantum dots in photonic bandgap hosts

Sharing Information:

We are planning to put this video on a website. In addition, our students will present these videos at the conferences and other meetings.

Product Type:

Course manuals

Product Description:

With the help of undergraduate students, we developed manuals for four teaching laboratories.

Sharing Information:

A website containing these manuals is under development.

Contributions

Contributions within Discipline:

(1) This project brought state-of-the-art photon-counting instrumentation and methods to the undergraduate laboratory and classroom. Photon-counting techniques exert enormous impact on advances in a wide range of fields,from astronomy and metallurgy to environmental protection, health diagnostics, medical analysis and imaging, and biomedical research.

(2) In addition, students will study most difficult concepts of quantum mechanics on the experimental setups for quantum informationon. This new field can revolutionize the lives of ordinary people with powerful quantum computers and absolutely secure quantum communication.

(3) A broad implication and impact on STEM education is the new method of teaching one of the most difficult and abstract concepts of modern physics which promise powerful quantum computers and absolutely secure quantum communication.

Contributions to Other Disciplines:

Our teaching laboratory is a multidisciplinary area. It includes quantum optics/quantum information science and technology, optical confocal single-molecule fluorescence microscopy, materials development. Our contributions to other disciplines are as follows:

(1) BIOMEDICINE
- Students investigated the new fluorescence markers (e.g., PbSe quantum dots) for 1.3 and 1.5 um spectral regions. Light of this spectral region has a great penetration depth inside the human body.

(2) NANOTECHNOLOGY
- Students developed photonic bandgap materials with tunable bandgaps using nanostructured liquid crystals.

(3)SINGLE-MOLECULE FLUORESCENCE MICROSCOPY
- Students participated in developing the methods of reducing fluorescence emitter bleaching in a host by special host treatment.

(4)LIQUID CRYSTAL MATERIAL SCIENCE AND TECHNOLOGY
- Students learned a new liquid crystal application which may have impact on optical communication technology.

Contributions to Human Resource Development:

This project contributed to human resource development in science, engineering and technology by involving students in building teaching experiments and training them on these setups.

Some 26 undergraduate students of Prof. Knox course participated in lecture-demonstration of teaching experiments.

6 students were enrolled in a full laboratory course which Dr. Lukishova taught during the Fall semester. Among students participated in this course were one woman and one minority undergraduate. Minority student continued to work on teaching laboratory during the Spring semester. 4 students (including one minority and one female) had publications from these teaching course.

Contributions to Resources for Research and Education:

One of the goal of this project is involving, consulting and informing others about our results during the course of the project and beyond.

We interacted with investigators working on similar or related approaches: Prof. E. Galvez (Colgate University), Prof. M. Beck (Whitman College), Prof. A. Zajonc (Amherst College), Prof. M. Fox (University of Sheffield, UK). Teaching laboratory experiments were shown to Prof. H. Gibbs (University of Arizona), Prof. T. Pittman (University of Maryland Baltimore County) and other visitors of the Institute of Optics.

We are organizing a workshop-symposium 'Quantum Optics and Quantum Engineering for Undergraduates' during the Annual Meeting of the Optical Society of America (Frontiers in Optics)/Laser Science Conference (Rochester, NY, October 23, 2008).

We submitted paper to workshop during Summer meeting of the AAPT (American Association of Physics Teachers)describing our teaching experiments.

Contributions Beyond Science and Engineering:

This project contributes to the public welfare beyond science and engineering. Two laboratory experiments with involvement of undergraduate students are devoted to a pivotal hardware element for quantum information (single-photon source).

In quantum communication, using single photon sources prevent an eavesdropper from being allowed to intercept, without the sender/receiver's knowledge, a message with secret encryption key. Any e-mail message, telephone call, credit card information and other financial transaction will be safe. They will be protected by the Heisenberg uncertainty principle.

Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Web/Internet Site

Project Activities and Findings

(June 07 – April 08)

Award No: EHR-0633621

CCLI-Phase I: Quantum Optics Laboratory for the Undergraduate Curriculum – Teaching Quantum Mechanics with Photon Counting Instrumentation

Carlos R. Stroud, Svetlana G. Lukishova, Wayne H. Knox

The Institute of Optics, University of Rochester, Rochester NY 14627

This three-year-project's goals are as follows:

- Curriculum improvement of the undergraduate education in Quantum Mechanics through adaptation and implementation of Quantum Optics/Information teaching laboratories and educational practices that have been already developed and tested by some European and North American Universities;
- Involvement of the undergraduate students in planning and decisions of building the teaching laboratory to increase feedback between teaching and learning;
- Involvement of undergraduate students in scientific process by using the research samples in the undergraduate teaching laboratory;
- Effective dissemination of project results to the broader community.

During the first year period of funding, our main **research and education activities** have been focused on following challenges:

- Developing and building four teaching experiments at the Institute of Optics, University of Rochester (S. Lukishova, C. Stroud, students L. Bissell and B. Zimmerman):
    - entanglement and Bell's inequalities;
    - single-photon source interference in Young's double-slit and Mach-Zehnder interferometers;
    - confocal fluorescence microscopy of single-emitter fluorescence;
    - Hanbury Brown and Twiss setup and fluorescence antibunching.
- Developing the manuals for these teaching experiments;
- Preparation and teaching the course on Quantum Optics and Quantum Information Laboratory (S. Lukishova) to six students from *three departments*;
- Meeting with Monroe Community College Vice President Janet Glocker and Dean Dianna Phillips regarding collaborative activities;
- Meeting with Corning Community College Professor T.A. Dunbar, discussion of his teaching experiments on modern optics and his involvement in our projects.
- Demonstration of four quantum optics experiments to 26 students of the course "Optics in the Information Age" (S. Lukishova, W. Knox);
- Demonstration of four quantum optics experiments to group of students of Colgate University visiting the Institute of Optics with their Prof. E. Galvez (We adapt and implement his experience on building and teaching photon quantum mechanics experiments);
- Evaluation of students' knowledge by questionnaires, report and essay writing, and oral presentations;
- Dissemination of results by writing papers and conference paper submission;

- Organizing future workshop-symposium "Quantum Optics and Quantum Engineering for Undergraduates" during the Annual Meeting of the Optical Society of America (Rochester, NY, October 23, 2008). We invited 5 speakers ("Undergraduate Quantum Optics: The Challenge and the Excitement"**,** *M. Fox, Univ. of Sheffield, UK***;** **"**A Quantum Optics Laboratory for Teaching Quantum Mechanics"**,** *E. J. Galvez, Colgate Univ*; **"**How to Write a Successful Educational Proposal to the NSF"**,** *W. W. Hein (NSF);* **"**Teaching Quantum Mechanics with Photon Counting Instrumentation"**,** *C. R. Stroud. G. Lukishova, Univ. of Rochester*; **"**The Challenges of Quantum Physics as Pedagogical Tools**,** *A. G. Zajonc, Amherst College*) and announced contributed oral and poster paper submission. After the symposium, all participants will be transported to the University of Rochester for a demonstration of the Quantum Optics and Quantum Information Teaching Laboratory at the Institute of Optics.
- Website preparation;
- Dissemination of results by demonstration of teaching experiments to Prof. E. Galvez (Colgate University) and professors from University of Arizona (H. Gibbs), Arizona State University (C-Z. Ning), University of Maryland, Baltimore County (T. Pittman).
- Students' research on room-temperature quantum-dot-doped liquid-crystal photonic-bandgap samples' development for efficiency increase of a single photon source (S. Lukishova)
- Sharing the new equipment with other research groups, for instance, (i) single-photon EM-CCD-camera has been used in students' research of R. Boyd's and J. Howell's groups on quantum optics; (ii) time-correlated single-photon-counting PC-card was used separately in the Laboratory for Laser Energetics, University of Rochester, both by students of R. Sobolewski in research on NbN receivers and in A. Schmid's nanometrology group;
- Evaluation of the first step of the project by the internal evaluator;
- In addition to current room (210 sq. feet), recently the Institute of Optics provided two rooms for the course labs (175.4 sq. feet and 242 sq. feet).
- Spectra-Physics donated a 250-mW UV argon ion laser with etalon inside for entanglement and Bell's inequality lab.

More details of our activities with the main results and findings are described below, in Parts 1-5 of this section of the Report. Here are the **highlights of these findings**:

Contribution to knowledge base outcome:

- Four teaching experiments were built at the Institute of Optics, University of Rochester (S. Lukishova, C. Stroud, students L. Bissell and B. Zimmerman):
    - entanglement and Bell's inequalities;
    - single-photon source interference in Young's double-slit and Mach-Zehnder interferometers;
    - confocal fluorescence microscopy of single-emitter fluorescence;
    - Hanbury Brown and Twiss setup and fluorescence antibunching.
- Manuals were written for four experiments with photon counting instrumentation.
- Students participated in this project co-authored one paper submitted to refereed journal, one conference proceeding and two submitted conference abstracts.
- Minority student Brandon Zimmerman participated in three national undergraduate symposia with oral presentations.
- We submitted a paper to the workshop during the Summer meeting of the AAPT, describing our teaching experiments.

Learning outcome:

- More than forty students benefited from these teaching experiments. Among them are students of three departments of the University of Rochester as well as students from Colgate University.
- Using questionnaire with 36 questions on photon quantum mechanics showed that one half from participated students answered correctly more than 75% of questions, 70% of students answered correctly more than 70% of questions and all students answered correctly more than 60% of questions.
- Students' mastery in photon-counting instrumentation is shown in that 50% of students received total scores of "A" and the rest of students received total scores of "A-". The grades were based on students' capability of carrying out the experiments, writing the reports and delivering oral presentations.

Community building outcome:

- We interacted with investigators working on similar or related approaches: Prof. E. Galvez (Colgate University), Prof. M. Beck (Whitman College), Prof. A. Zajonc (Amherst College), Prof. M. Fox (University of Sheffield, UK).
- Teaching experiments were shown to Prof. Gibbs (University of Arizona), Prof. T. Pittman (University of Maryland Baltimore County) and other visitors of the Institute of Optics.
- A Workshop-symposium "Quantum Optics and Quantum Engineering for Undergraduates" was included in the program of the Annual Meeting of the Optical Society of America (Frontiers in Optics)/Laser Science Conference (Rochester NY, October 23, 2008).
- Prof. Stroud delivered lectures on public colloquium at the Case Western Reserve University entitled "Visualization and control of atomic electrons" and for general public at the Laboratory for Laser Energetics S&T seminar entitled "The history of optics at the University of Rochester".

Below is a more detailed description of some above-mentioned findings. This first year of the project was devoted to building four teaching labs, writing their manuals, starting teaching of the course, starting of data collection for evaluation of students' knowledge and the first evaluation of new labs by the internal evaluator.

1. DESCRIPTION OF PREPARED TEACHING EXPERIMENTS

Lab. 1. Entanglement and Bell's inequalities

The schematic of teaching experiment to produce polarization-entangled photons and Bell's inequalities' violation measurements is shown in the Figure 1, left. We implemented and developed the setup of D. Dehlinger and M.W. Mitchell [*Am. J. Phys*., **70** (9), 898 (2002)].

In this experiment, we use spontaneous parametric down conversion process in two type-I BBO crystals. Light from a 10 mW, 405 nm cw pump diode laser passes through a blue filter and then a quartz plate. A mirror re-directs the beam through a pair of BBO crystals that are mounted back-to-back with one rotated 90^o from the other about the beam propagation direction. Down-converted photons from the crystals are detected by a pair of single-photon counting avalanche photodiode modules (APDs) mounted on the rails. This enables these two APDs to be on two diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization.

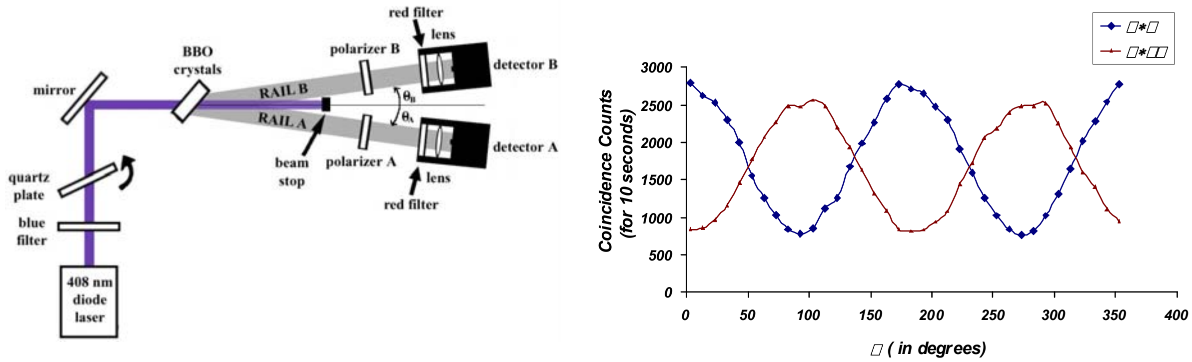


Figure 1. Left: Schematics of entanglement and Bell's inequalities experiment Right: Experimental polarization correlation's.

A 45^o polarized pump photon can downconvert in either crystal, producing a polarization entangled pair of photons. Quartz plate rotation compensates phase Δ introduced by the crystals.

$$|H\rangle + |V\rangle \rightarrow |V_s V_i\rangle + \exp(i\Delta)|H_s H_i\rangle$$

Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, right shows $\sim\cos^2(\alpha-\beta)$ coincidence count dependence on a relative angle $\alpha-\beta$ between two linear polarizers A and B located in front of each APD. In this experiment an angle β of the linear polarizer B varies at two different fixed angles α of the polarizer A. Calculation of Bell's inequality in the Clauser-Horn-Shimony-Holt form shows its violation (S~2.65 > 2).

Figure 2. Students M. Malik (Department of Optics) and P. Li (Department of Electrical and Computer Engineering) work on an entanglement and Bell's inequality experiment.

Lab 2. Single photon interference (Young's double slit experiment and Mach-Zehnder interferometer)

Young's double slit experiment with single photons shows wave-particle duality. Measurements were made using He-Ne laser beam, attenuated to a single photon level and EM. cooled CCD camera iXon of Andor Technologies (Figure 3, left). Mach-Zehnder interferometer (Figure 3, right) is used for the demonstration of a single-photon interference after removing "which-way" information (identification of the path).

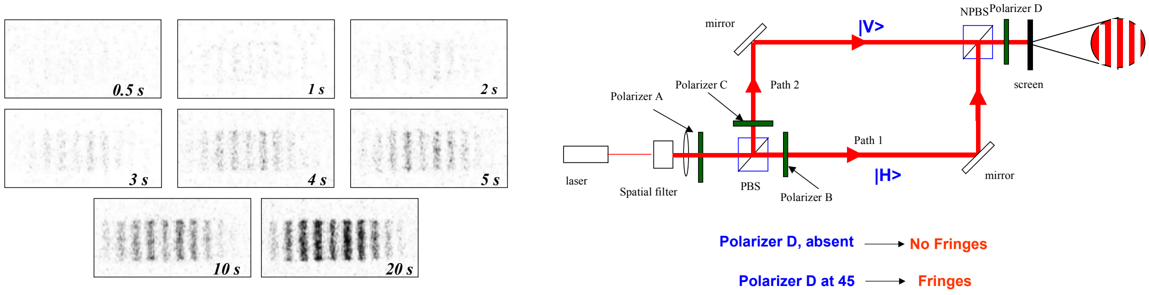


Figure 3, Left: Single-photon interference using Young's double-slit at different exposure time. Right: Mach-Zehnder interferometer schematics for "which-way experiment

Figure 4. Student B. Zimmerman (Department of Optics) and teaching assistant L. Xu work on a single-photon interference experiment.

Lab 3. Confocal microscope imaging of single-emitter fluorescence

8 ps pulse duration, 76 MHz pulse repetition rate excitation at 532-nm was used for confocal microscope single-emitter fluorescence imaging (Figure 5). DiI dye or colloidal semiconductor quantum dots were used as emitters.

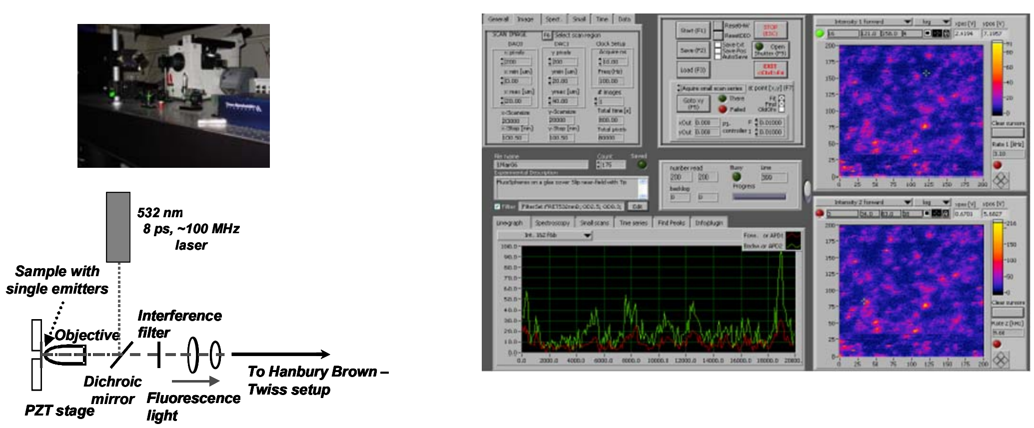


Figure 5. Left: Photograph and schematic of a home-built confocal microscope; right: User interface for single-emitter fluorescence imaging. Images of a raster scan of the sample show DiI-dye single-molecule fluorescence.

Students enrolled in the laboratory course also participated in research. They carried out imaging of single PbSe quantum dot fluorescence in photonic bandgap cholesteric liquid crystal host (Figure 6, left shows “blinking” of quantum dot). PbSe quantum dots are very important for single-photon source operating at optical communication wavelengths. Figure 6, right shows a group of students working on this project.

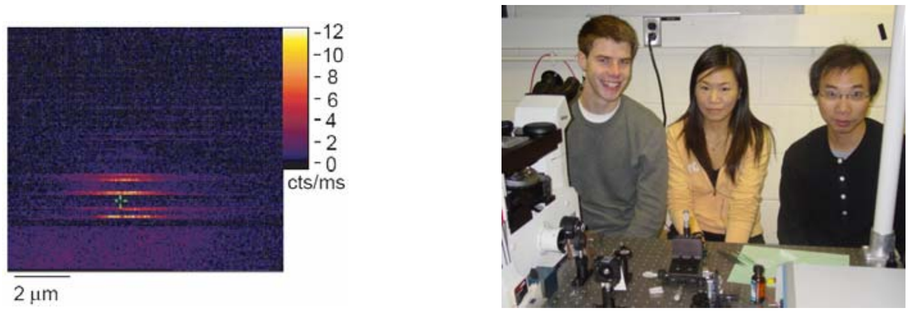


Figure 6. Left: Single PbSe quantum dot fluorescence image in 1-D photonic bandgap liquid crystal host (800 nm fluorescence maximum); right: students working on this project - C. Clarkson (Department of Electrical and Computer Engineering), Y.J. Choi and X.-F. Qian (Department of Physics and Astronomy).

Lab. 4. Hanbury Brown and Twiss setup. Fluorescence antibunching

We were able to record changes of fluorescence intensity of single quantum dot in time (Figure 7, left). Figure 7, right shows Hanbury Brown and Twiss setup for fluorescence antibunching measurements. It consists of a nonpolarizing 50:50 beamsplitter forming two arms. The time interval τ between two consecutively detected photons in separate arms is measured by a TimeHarp 200 PC time-correlated single-photon counting card using a conventional start-stop protocol. This coincidence-event distribution is proportional to the autocorrelation function $g^{(2)}(\tau)$. For single photons, $g^{(2)}(0)=0$ indicating the absence of pairs, or antibunching. Figure 8 shows antibunching curves with the dips at $\tau = 0$ indicating antibunching. The antibunching dip at time interval $\tau = 0$ on the correlation events histogram is a proof of the single-photon nature of the source.

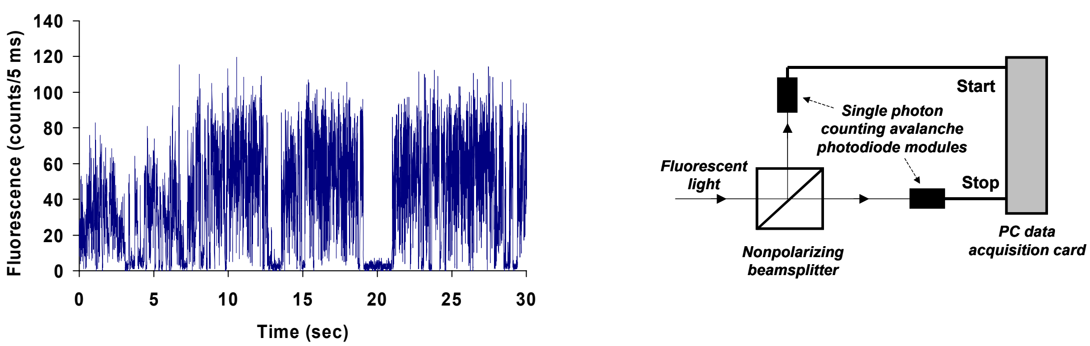
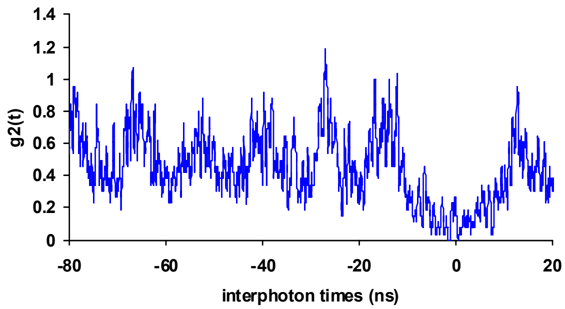


Figure 7. Left: Schematics of Hanbury Brown and Twiss setup for fluorescence antibunching measurements, right – changes of fluorescence intensity of single CdSeTe quantum dot in time (blinking).



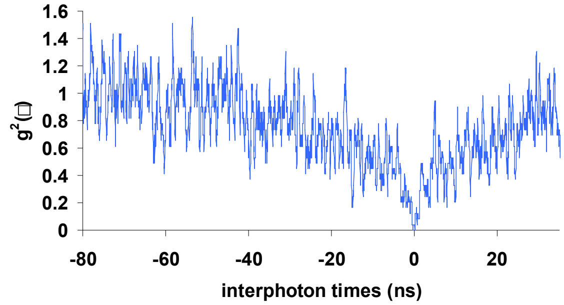


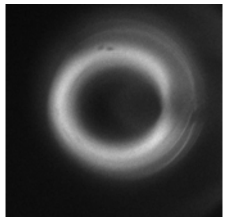
Figure 8, Left: Fluorescence antibunching of single PbSe quantum dot on bare glass slip under pulsed laser excitation (850 nm maximum fluorescence); right: fluorescence antibunching of single CdSeTe quantum dot in 1-D photonic bandgap cholesteric liquid crystal host (fluorescence lifetime of quantum dots is higher than the time interval between laser pulses).

2. PROVIDED OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

Training of six students from three departments of the University of Rochester was accomplished during the first year of the project (Fall semester). These students were enrolled in the course "Quantum Optics and Quantum Information Laboratory" (Lukishova). All students carried out four teaching experiments, wrote reports and essay, delivered oral presentations and answered questionnaires. They worked six hours per week during 15 weeks in groups of two or three students. Two teaching assistants of the course were also trained on these equipment (Detailed description of the experiments is presented in previous section). One student from this course (Brandon Zimmerman) continued to work on the project selecting it as his research project. He delivered talks at three national undergraduate symposia as well as at the Conference of the National Society of Black Engineers (students' chapter). Four students of the course were selected as co-authors in refereed publications (one journal submission and one published conference proceeding).

In addition, some 26 students of the Institute of Optics enrolled in the course "Optics in the Information Age" (Knox) participated in a lecture-demonstration of these laboratory experiments. This demonstration provided students a laboratory experience with the concepts that they studied on the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.) Approximately ten students of Colgate University and five high-school students participated in similar demonstration.

Some equipment of Lab. 3, EM-CCD camera is practically in use almost every day in the students' research both of PI and co-PI groups and by students of other groups. For example, in our collaborative research with Prof. Boyd (Department of Optics) and S.-H. Chen (Department of Chemistry) on dye-doped cholesteric liquid crystal laser this camera was used by students to record the spatial distribution at the output of cholesteric laser with a *high dynamic range*. Figure 9, left shows the results of using EM-CCD-camera by Boyd's students working on polarization entangled photons. It is easy to see spontaneous parametric down conversion cones of photons at the output of type II BBO crystal using this device.



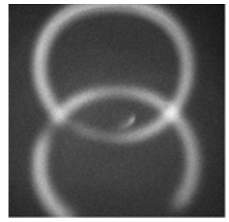


Figure 9. Example of student training results: spontaneous parametric down conversion cone of photons at the output of type I (left) and type II BBO crystals (right).

Faculty of different Universities visited Quantum Optics and Quantum Information teaching experiment facility learning the experience of the Institute of Optics. Among them were Prof. Gibbs (University of Arizona), Prof. T. Pittman (University of Maryland Baltimore County), and Prof. E. Galvez (Colgate University), Prof. T. Dunbar (Corning Community College).

3. OUTREACH ACTIVITIES

1. Prof. Stroud delivered a lecture for general public at the Laboratory for Laser Energetics S&T seminar entitled 'The history of optics at the University of Rochester' (October 2007).
2. Prof. Stroud delivered a lecture on Public Colloquium at the Case Western Reserve University entitled 'Visualization and control of atomic electrons' (April 9, 2008).
3. Undergraduate minority student Brandon Zimmerman delivered four lectures about the role of adiabatical following in classical and quantum mechanics and single-photon detection using single-emitter fluorescence at the following conferences:
   - Annual McNair Undergraduate Research Conference (University of Maryland, Baltimore County, Fall 2007);
   - National Society of Black Engineers, Annual Fall Regional Research Conference (Fall 2007);
   - National Conference for Undergraduate Research (Maryland, Spring 2008);
   - National Undergraduate Students in Technical Research Competition (Orlando, Florida, Spring 2008).
4. Graduate student Luke Bissell participated in optical experiment outreach activity with high-school students (Spring 2008).

4. INITIAL STEP OF EVALUATION OF STUDENTS' KNOWLEDGE AND LABORATORY COURSE SUCCESS

To monitor students' activity in the classroom as well as to evaluate students' knowledge and course success, we used both formative and summative evaluation techniques which tell us (1) whether students like these labs and what needs to be improved; (2) whether students mastered particular concepts. In addition, to satisfy the National Science Standards [National Research Council (Washington, DC, 1996] we took some methodology from the paper of E. Etkina, A.

Van Heuvelen et al. [“Scientific abilities and their assessment”, Phys. Rev. Spec. Topics – Phys. Educ. Research, 2, 020103 (2006)], in particular we taught students (i) recognize and analyze alternative explanations and models and (ii) communicate and defend a scientific argument. Director and coordinator of the Teaching Laboratories of the Institute of Optics P. Adamson led in efforts of internal evaluation of the project. We will use the help of external evaluators when the project will be stabilized.

Formative evaluation was carried out by six students enrolled in the laboratory course taught by Lukishova. These evaluations took place both in oral (after each lab) and in written (after the whole course) forms. All students evaluated the course very positive that indicates the success of the course. The main improvements of the course should be in more intensive homework tasks. Some students wanted to build experimental set-ups from scratch.

Summative evaluation was accomplished by two ways: (1) using different questionnaires (without grading) and (2) using the grades for each lab. Two teaching assistants helped in summative evaluation.

For instance, using questionnaire with 36 questions on photon quantum mechanics showed that one half students answered correctly more than 75% of questions, 70% of students answered correctly more than 70% of questions and all students answered correctly more than 60% of questions. It shows the success in students’ learning. During the discussion of questionnaires with each student separately, students were asked to defend their scientific arguments because some questions permitted different types of answers.

Students’ mastery in photon-counting instrumentation showed that 50% of students received total scores of “A” and the rest of students received total scores of “A-“. The grades were based on students’ capability of carrying out the experiments, writing the reports, and delivering oral presentations.

To recognize and analyze alternative explanations and models students were asked to write the essays on alternative technologies to single-photon sources based on single colloidal quantum dot fluorescence.

For communication skills development students were divided into groups (two or three students in each group depending on particular lab). Each group of students presented a single report written by all group members although students within each group can received different grades for the lab. The grade also depended on students’ activity and knowledge during the whole lab. Before each lab students were asked and were able to ask their instructor any questions.

5. PUBLICATIONS AND PRESENTATIONS

5.1. Journal publications and periodically published conference proceedings

1. S.G. Lukishova, L.J. Bissell, V.M. Menon, N. Valappil, M.A. Hahn, C.M. Evans, B. Zimmerman, T.D. Krauss, C.R. Stroud, Jr., R.W. Boyd, ”Organic photonic bandgap microcavities doped with semiconductor nanocrystals for room-temperature single photon sources on demand”, J. Modern Optics, Special issue on Single Photon, 2008 (submitted).

2. S.G. Lukishova, L.J. Bissell, C.M. Evans, M.A. Hahn, Y.J. Choi, C.J. Clarkson, X.F. Qian, T.D. Krauss, C.R. Stroud, Jr., R.W. Boyd, "Visible and telecom-wavelength single quantum dots in 1-D photonic bandgap chiral microcavities", Proceed. of the Quantum Electronics and Laser Science Conference (CLEO/QELS 2008, Optical Society of America, May 4-9, San Jose, CA, paper QFA5.

5.2. One-time publications in conference proceedings

3. C.R. Stroud and S.G. Lukishova, "Teaching quantum mechanics with photon counting instrumentation", Invited presentation, Annual Meeting of the Optical Society of America (Frontiers in Optics)/Laser Science Conference, Symposium-workshop "Quantum Optics and Quantum Engineering for Undergraduates" (Rochester, NY, October 23, 2008).
4. S.G. Lukishova and C.R. Stroud, "Quantum optics and quantum information teaching laboratory", submitted to the workshop (postdeadline) "Photon Quantum Mechanical Labs" of AAPT 2008 Summer Meeting (Edmonton, Alberta, CA, July 19-23, 2008).
5. C.R. Stroud and S.G. Lukishova, "CCLI-PHASE I: quantum optics laboratory for the undergraduate curriculum – teaching quantum mechanics with photon counting instrumentation", Poster presentation, National Science Foundation, CCLI PI Conference, Washington D.C., August 13-15 (2008), accepted.
6. S.G. Lukishova, C.R. Stroud, Jr., L.J. Bissell, B. Zimmerman, W. H. Knox, "Teaching experiments on photon quantum mechanics", Annual Meeting of the Optical Society of America (Frontiers in Optics)/Laser Science Conference, Symposium-workshop "Quantum Optics and Quantum Engineering for Undergraduates" (Rochester, NY, October 23, 2008), poster presentation, submitted.

c) Other lectures and presentations

7. C.R. Stroud, Jr., "The history of Optics at the University of Rochester", Public lecture at the Laboratory for Laser Energetics, S&T seminar (October 2007).
8. C.R. Stroud, Jr., "Visualization and control of atomic electrons", Case Western Reserve University, Public Colloquium (April 9, 2008).
9. B. Zimmerman, "Quantum tennis", Annual McNair Undergraduate Research Conference (University of Maryland, Baltimore County, Fall 2007).
10. B. Zimmerman, "Quantum tennis", National Society of Black Engineers, Annual Fall Regional Research Conference" (Fall 2007).
11. B. Zimmerman, "Quantum tennis", National Conference for Undergraduate Research (Maryland, Spring 2008).
12. B. Zimmerman, "Research on quantum tennis and single-photon source", National Undergraduate Students in Technical Research Competition (Orlando, Florida, Spring 2008).