Annual Report for Period: 09/2009 - 08/2010 **Submitted on:** 08/31/2010

Principal Investigator: Stroud, Carlos R. **Award ID:** 0920500

Organization: University of Rochester

Submitted By:

Lukishova, Svetlana - Co-Principal Investigator

Title:

Collaborative Research - CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics 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 teaches the course OPT 223 'Quantum theory of optics' for undergraduate students (seniors). In this course two 3-hour quantum optics laboratories were introduced for each student (four groups of students).

Name: D'Alessandris, Paul

Worked for more than 160 Hours: Yes

Contribution to Project:

Paul D'Alessandris from MCC (Monroe Community College) (Rochester, NY), a co-Principal Investigator, taught Modern Physics course. He jointly with Svetlana Lukishova taught 3-hour quantum optics laboratory for 3 groups of MCC students at the University of Rochester laboratory facility. He developed teaching methods for community college students, collected and evaluated data on students' knowledge after the labs.

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 as well as their research. She developed teaching strategy, wrote the manuals and evaluated students' knowledge (jointly with internal and external evaluators). Her teaching activities on this project are as follows:

(1) Teaching 4-credit hour course 'Quantum Optics and Quantum Information Laboratory;

(2) Teaching labs for OPT 223 Quantum Theory of Optics (two three hour labs);

(3) Teaching labs for Monro Community College students jointly with their professor P. D'Alessandris (two 3 hour labs)

(4) Teaching two lab research project of two groups of freshmen (OPT 101 Optics in Information Age - Prof. Knox).

She also collaborated with Prof. R. Jodoin (Rochester Institute of Technology) during his sabbatical in her teaching lab.

Name: Jodoin, Ronald

Worked for more than 160 Hours: Yes

Contribution to Project:

Ronald Jodoin (Rochester Institute of Technology, RIT) is a co-Principal Investigator. During the Fall semester he worked on his sabbatical in Svetlana Lukishova's laboratory on entanglement and Bell's inequolity setup. He improved alignment of the system and methods of entangled photon registration. His goal is to establish Quantum Optics Teaching Laboratory at RIT.

Name: Knox, Wayne

Worked for more than 160 Hours: Yes

Contribution to Project:

Prof. Wayne Knox teaches freshmen course OPT101 Optics in Information Age. After evaluation of students' questionnaires from Phase I grant, he introduced in his course laboratory research projects. Two groups of freshmen carried out their 12-hour research projects in quantum optics labs of Dr. Lukishova.

Name: Galvez, Enrico

Worked for more than 160 Hours: Yes

Contribution to Project:

Prof. Enrico Galvez (Colgate University) helped us to evaluate student knowledge.

Name: Belyakov, Vladimir

Worked for more than 160 Hours: Yes

Contribution to Project:

Vladimir Belyakov (Landau Institute for Theoretical Physics, Moscow, Russia) helped us with understanding of beam propagation in chiral photonic bandgap structures which our students prepared during their labs. He also wrote a manuscript for us for easy explanation of beam propagation in such structures.

Post-doc

Graduate Student

Name: Lapin, Zack

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student Zack Lapin was a teaching assistant of 4-credit hour laboratory course 'Quantum Optics and Quantum Information Laboratory'. He also developed and maintained a website of the course and helped in evaluation of students' knowledge.

Name: Bissell, Luke

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student Luke Bissell developed several elements of experimental setup for single photon source. He also taught students how to prepare samples for single photon source lab.

Name: Gao, Boshen

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student Boshen Gao was a teaching assistant of OPT 223 course 'Quantum Theory of Optics'. He also taught one of 3-hour labs attached to the course and helped in evaluation of students' knowledge.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Colgate University

Prof. Enrico Galvez (Colgate University) helped us to evaluate students' knowledge.

Landau Institute for Theoretical Physics

Prof. V. Belyakov from Landau Institute for Theoretical Physics (Moscow, Russia) worked on beam propagation in chiral photonic bandgap structures which are used in single-photon source lab of Quantum Optics and Quantum Information Laboratory course. He wrote a manuscript for the project how to explain students beam propagation in chiral photonic bandgap structures. He visited labs in Rochester and discussed with Prof. Stroud and Dr. Lukishova his notes written for our project.

Other Collaborators or Contacts

Through Optical Society of America we had contacts with several scientists who are interested in the teaching labs, e.g., Dr. Pramode Verma (Williams Chair in Telecom Networking & Director, Telecom. Eng. Program The University of Oklahoma-Tulsa) contacted Dr. Lukishova with invitation to give a seminar about Quantum Optics Labs. This talk is scheduled on September 2010.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
SEE ATTACHED FILE FOR MAJOR RESEARCH AND EDUCATIONAL ACTIVITIES AND FINDINGS

Findings:
SEE ATTACHED FILE FOR MAJOR RESEARCH AND EDUCATIONAL ACTIVITIES AND FINDINGS

Training and Development:
(1) Students at diverse educational institutions obtained research skills in photon quantum mechanics and modern physics experiments.

(2) Students obtained skills in photon-counting instrumentation that is widely used in quantum information technology and biomedical research;

(3) Students received experience in planning, making decisions and carrying out research experiments in quantum optics;

(4)Students received experience in presentation of their results and explanations of these results to other students

SEE ALSO ACTIVITIES AND FINDINGS FILE for more details.

Outreach Activities:
1. Lecture-demonstrations of quantum optics laboratory to 35 Brighton high-school students and teachers (Knox, Lukishova);

2. Stroud delivered lectures on 'Quantum weirdness' in several Universities (Undergraduate colloquium - University of Puget Sound - Sept 2009; Public Lecture - Pacific Lutheran University - Sept 2009; Stookey Award Lecture - Corning, Inc. - Oct 2009; Keynote Address - Annual meeting of New York Science, Engineering and Technology Association; Corning Community College, October 2009; Welcoming Address - Symposium on Quantum Engineering - University of Rochester, Oct. 2009).

3. Lukishova was invited this September to the University of Oklahoma (Tulsa) to give a talk as well as to discuss challenges in organizing quantum optics laboratory.

Journal Publications

L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr., and R.W. Boyd, "Chiral photonic bandgap microcavities doped with single colloidal semiconductor quantum dots", ProceedingsPIE, p. , vol. , (2010). Accepted,

L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr., and R.W. Boyd, "Room-temperature single photon sources with definite circular and linear polarizations based on single-emitter fluorescence in liquid crystal hosts", Proceedings SPIE, p. , vol. , (2010). Accepted,

S.G. Lukishova, L.J. Bissell, C.R. Stroud, and R.W. Boyd, "Room-temperature single photon sources with definite circular and linear polarizations", Optics and Spectroscopy, Springer, p. 452, vol. 108, (2010). Published,

M.A. Landau and C. R. Stroud, Jr., "Calculation of the convex roof for an open entangled harmonic oscillator system", Phys. Rev. A, p. 052304, vol. 81, (2010). Published,

H. Nihira and C. R. Stroud, Jr., "Steady-state two-atom entanglement in a pumped cavity", Phys. Rev. A, p. 042329, vol. 80, (2009). Published,

Books or Other One-time Publications

L. Bissell
(Advisors: C.R. Stroud and S.G. Lukishova)
, "Room-Temperature, On-Demand
Single-Photon Sources", (2010). Thesis, Submitted
Editor(s): University of Rochester
Collection: Ph.D Thesis Proposal
Bibliography: University of Rochester, the Institute of Optics

L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn,
C.M. Evans, T.D. Krauss, C.R. Stroud, Jr, and R.W. Boyd
, "Room-temperature single photon sources
with definite circular and linear polarizations based
on single-emitter fluorescence in liquid crystal hosts", (2010). Conference Proceedings, Accepted
Editor(s): International Conference on Coherent and Nonlinear Optics, Kazan', Russia
Collection: Nanophotonics and Plasmonics
Bibliography: Kazan', Russia, 23-26 August 2010

L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn,
C.M. Evans, T.D. Krauss, C.R. Stroud, Jr, and R.W. Boyd
, "Chiral photonic bandgap microcavities doped with single colloidal semiconductor quantum
dots", (2010). Conference Proceedings, Accepted
Editor(s): International Conference on Coherent and Nonlinear Optics, Kazan', Russia
Collection: Nanophotonics and Plasmonics
Bibliography: Kazan', Russia, 23-26 August 2010

S.G. Lukishova, L.J. Bissell, C.R. Stroud, Jr., "Photonic Band-Edge Circular Polarized Microcavity Resonances in Glassy Chiral Liquid Crystals under CW-Irradiation", (2010). Conference Proceedings, Accepted
Editor(s): Optical Society of America
Collection: 2010 Frontiers in Optics (FiO)/Laser Science XXVI (LS) Conference, October 24-28, 2010, Rochester, New York, USA.
Bibliography: paper FThQ1

Web/Internet Site

URL(s):

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

Description:

This site is devoted to Quantum Optics and Quantum Information Laboratory and directly relates to the award. It was started with our Phase I project and maintains by graduate students participating in the project. It contains lab manuals, lectures and presentations, student reports and other relevant materials to the project.

It is linked to the NSF funded educational site www.thequantumexchange.org.

Other Specific Products

Product Type:

Audio or video products

Product Description:

Our students prepared the following videos using low-light level EM-CCD-cameras: (1)on fluorescence of single quantum dots in photonic bandgap hosts, (2) on spontaneous parametric down conversion cones from type I BBO crystals (entangled photon generation).

Sharing Information:

These video are constantly demonstrated during our lectures and outreach talks as well as during quantum optics lab visits by groups of students (university, high-school, community college) and other visitors from different universities and colleges.

Product Type:

Instruments or equipment developed

Product Description:

With participation of undergraduate students (including freshmen) we developed single photon source instrument. As fluorescent emitters we use single NV-color centers in nanodiamonds, single colloidal quantum dots and single dye molecules. We also added spectral diagnostics to this instrument.

Sharing Information:

This instrument is in use by other groups of our University, e.g., by Prof. Boyd and his students. This instrument is in use in different courses of Departments of Optics and Physics (OPT 253/OPT453/PHY434, OPT101, OPT223).

Product Type:

Teaching aids

Product Description:

We created manuals for each quantum optics labs and educational lecture materials on entanglement.

Sharing Information:

All manuals and lecture are placed to the website http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

linked with NSF supported www.thequantumexchange.com. We have 1693 visitors of our website. Some people ask questions through e-mails.

Product Type:

Teaching aids

Product Description:

Questionnaires for evaluation of students'knowledge on (1) entanglement and Bell's inequalities, (2) single photon interference and (3) single photon sources

Sharing Information:

We put questionnaires for different student levels on evaluation of students' knowledge on our website http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

Contributions

Contributions within Discipline:

(1) This project brought state-of-the art quantum optics and nanotechnology methods and instrumentation to the undergraduate laboratory and classroom of several different institutions (University of Rochester with strong programs on Quantum Mechanics and Quantum Optics and Nanotechnology, Community College and Technical University preparing students for industry).

(2) Reducing to practice some of the most abstract components of quantum mechanics by allowing the students to carry out experiments at a range of levels connected with modern applications, in particular, quantum computing and quantum communication.

(3) A broad implication and impact on STEM education of students of different levels in different types of educational institutions 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:

Quantum Optics and Quantum Information teaching laboratory which we develop is a multidisciplinary research and teaching laboratory. It includes equipment and tools for quantum optics/quantum information science and technology, optical confocal single-molecule fluorescence microscopy, nanophotonics and nanotechnology and materials' development. Our contributions to other disciplines are as follows:

(1) BIOMEDICINE

- Students investigate the new fluorescence markers (e.g., nanodiamonds with color centers, quantum dots (including PbSe quantum dots for

1.3 and 1.5 um spectral regions with a significant penetration depth inside the human body).

(2) NANOPHOTONICS AND NANOTECHNOLOGY
- Students develop photonic bandgap structures with tunable bandgaps using liquid crystal materials;
- Students study different types of nanoemitters.

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

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

Contributions to Human Resource Development:

(1) This project contributed to human resource development in science, engineering and technology by involving students of different levels of different types of educational institutions in building teaching experiments and training them on these setups.

(2) During the first year of this project, 7 students were enroled in a four-credit hour laboratory course which Dr. Lukishova taught during the Fall 2009 semester. Among students participated in this course were two women and one Hispanic student.

(3) 14 students from Monroe Community College carried out this Spring two three hour labs at the University of Rochester. Among them were two minority students and two women.

(4) 17 students of Spring Optics course 'Quantum Mechanics of Optical Materials and Devices' (Stroud), divided by four groups, carried out two 3-hour labs. Among them were three women and one minority student.

(5) 10 freshmen divided in two groups of Optics course 'Optics in Information Age' (Knox) carried out their 12-hour-research projects on single photon source and single photon interference. Among them was one woman.

(6) 25 freshmen of Knox's course 'Optics in Information Age' (four groups) participated in lecture-demonstrations of teaching experiments.

(7) Jodoin from Rochester Institute of Technology (RIT) spent his Fall 2009 sabbatical developing entanglement teaching lab that he will introduce at RIT.

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.

In addition to our website, manuals, lecture materials, questionnaires and video developments reported in Specific Products section, our other contributions for research and educations are as follows:

(1) We interacted with investigators working on similar or related approaches: Prof. E. Galvez (Colgate University), Prof. M. Beck (Whitman College). We sent description of our projects to experts working in science education: Prof. Van Heuvelen, Rutgers University) and Prof. Laird Kramer (Florida International University, Miami.
Teaching laboratory experiments were shown to Prof. V. Belyakov (Landau Institute for Theoretical Physics, Moscow), Prof. A. Aspect (Institute d'Optique, Paris), Prof. F. Capasso (Harvard University) and other visitors of the Institute of Optics.

(2) We published and submitted 5 papers in journals, 2 papers in conference proceedings and prepare invited presentation at the University of Oklahoma (Tulsa).

(3) P.D. Thesis proposal (Bissell) was submitted (Lab 3-4).

Contributions Beyond Science and Engineering:

This project contribute to the public welfare beyond science and engineering. All teaching laboratory experiments are devoted to a pivotal concepts of quantum information that can revolutionize the life of ordinary people. For example, in quantum communication, using single or entangled photons 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, protected by laws of quantum physics. In addition, powerful quantum computers can solve many unsolvable problems today.

Conference Proceedings

Special Requirements

Special reporting requirements: None
Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Conference

Project Activities and Findings

<u>First Year (June 09 – May 10) Award No: 0920500</u>

Collaborative Research – CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation

Carlos R. Stroud, and Svetlana G. Lukishova
The Institute of Optics, University of Rochester, Rochester NY 14627
Pail D'Alessandris
Monroe Community College
Ronald Jodoin
Rochester Institute of Technology

Goals and Objectives (4-year project)

The central task of this project is the development of a set of 1.5 - 3 hour teaching experiments for quantum mechanics and modern physics courses at a diverse range of colleges and Universities. The project will impact the curricula of three Departments of the University of Rochester (UR), two community colleges (Monroe and Corning), liberal art college for women, Bryn Mawr, Rochester Institute of Technology, Adelphi University, and two other colleges that will be identified after a 4th year workshop. The project goals are as follows:

(1) Improvement of student learning at these *diverse* educational institutions in quantum mechanics and modern physics. The basis for achieving this goal is the experience of the UR (Phase I project) and educational practices from the STEM educational knowledge base on photon quantum mechanics teaching laboratories;

(2) Providing photon-counting instrumentation skills to the future workforce;

(3) Increasing feedback between teaching and learning by involving undergraduate students in planning and decisions during building the teaching laboratory;

(4) Involvement of undergraduate students in the research process by using research setups and samples in the undergraduate teaching laboratory;

(5) Effective dissemination of project results to the broader education community and contribution to the STEM educational knowledge base.

During the first year period of funding three institutions worked on the initial tasks of the project: University of Rochester, Rochester Institute of Technology and Monroe Community College. **<u>Our main research and education activities have been focused on the following challenges:</u>**

- Developing "mini-labs" (three-hour versions for teaching experiments built during the Phase I project): (1) entanglement lab; (2) single-photon interference lab; single photon source labs: (3) single emitter confocal fluorescence microscopy; (4) fluorescence antibunching, and Hanbury Brown-Twiss interferometer.
- Developing independent program of quantum optics teaching experiments at the Rochester Institute of Technology (RIT) using the experience gained at the UR. Prof. Jodoin, co-PI of the project, spent his Fall 2009 sabbatical at the UR working with Dr. Lukishova on one of the versions of the entanglement lab which can be implemented at RIT, as well as on single

photon interference lab. Under the mentoring of Lukishova Jodoin performed existing experiments on single photon interference and a test of Bell's inequality using quantum entanglement. With this background and experience he worked on a new setup to do quantum entanglement using a blue diode laser as the source for parametric down-conversion. This involved aligning the optics and assembling and testing a new coincidence counter that interfaced to a computer using LabView.

- As an additional educational experience for RIT, Jodoin audited Stroud's course on quantum optics and attended several colloquia hosted by the Institute of Optics.
- Jodoin is currently developing the laboratory portion of a new quantum optics course at RIT. His colleague in the Physics Department, Edwin Hach, is designing the lecture part of the course. They are collaborating with Stefan Preble in the Microsystems Engineering Program, who is supplying some of the needed equipment. For the RIT laboratories Jodoin has designed four experiments based on those that he did at the Institute of Optics (UR). They are (1) single photon interference, (2) the quantum eraser, (3) characterization of parametric down-conversion, and (4) a test of Bell's inequality. The equipment is currently in house or being purchased so that the course can be offered next academic year.
- To prepare typical physics undergraduates at RIT for the experiments, Jodoin has written a comprehensive set of pre-laboratory notes. These include the history and significance of the experiments and mathematical derivations of the results expected from quantum theory.
- Developing lecture materials on entanglement and Bell's inequalities to facilitate students' understanding of labs [Lukishova, Jodoin, Stroud in collaboration with Eberly (Department of Physics, UR)];
- Developing and teaching 4-credit-hour course on Quantum Optics and Quantum Information Laboratory (Lukishova) to seven students from *three departments*;
- Preparation and teaching of two "mini-labs" labs at the UR facilities to 3 groups of 14 students of Monroe Community College (MCC). Entanglement lab was taught by Lukishova (UR), single photon interference lab – by D'Alessandris (MCC).
- Preparation and teaching two "mini-labs" to 4 groups of 17 seniors of the UR lecture course "Quantum mechanics of optical materials and devices" (Stroud). Entanglement lab was taught by Lukishova, single photon interference lab – by a TA.
- 12-hour freshmen research projects of "Optics in the Information Age" course (2 groups of 10 students) on room-temperature single photon source and single photon interference (Lukishova, Knox);
- Students' research on room-temperature polarized single photon source (Lukishova)
- Lecture-demonstrations of four quantum optics experiments to 25 students of the course "Optics in the Information Age" (Lukishova, Knox);
- Lecture-demonstrations of quantum optics experiments to 3 groups of 35 high-school students and their teachers;
- Sharing the new equipment with other research groups, for instance, (i) single-photon EM-CCD-camera, Newport picometer has been used in students' research of Boyd's group on

quantum optics. Boyd's students carried out a research project using the confocal microscope setup with antibunching measurements (Labs 3-4). Novotny's students used the entanglement setup and EM-CCD-camera for their research project.

- Evaluation of students' knowledge by questionnaires, report and essay writing, and oral presentations. Evaluation of the first step of the project by the internal evaluator;
- Dissemination of results by writing papers and conference paper submission;
- Website preparation of the course "Quantum Optics and Quantum Information Laboratory (http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab). Linking this website with NSF supported the Quantum Exchange and ComPadre sites.
- Dissemination of results by demonstration of teaching experiments to Prof. E. Galvez (Colgate University), professors Capasso (Harvard University), Aspect (Institute D'Optique, France), Belyakov (Landau Institute for Theoretical Physics, Russia), and other visitors of the Institute of Optics (UR);
- In addition to current rooms for teaching labs (210 sq. feet, 175.4 sq. feet and 242 sq. feet), the Institute of Optics provided an office room (175.4 sq. feet) which was used by visitors and collaborators.
- Outreach activities (see details below).

More details of our activities with the main results and findings are described below.
<u>Here are the highlights of these findings:</u>

Contribution to knowledge base outcome:

- Four teaching experiments in quantum mechanics and modern physics are in development by UR, RIT and MCC for students of *diverse* educational institutions. (Lukishova, Stroud, Jodoin, D'Alessandris, graduate student Bissell, undergraduate students):
    - 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.
- Lecture materials on entanglement and Bell's inequalities for facilitation of student's understanding were prepared after intensive discussions with leading quantum optics scientists and teachers.
- Students participated in this project co-authored one published paper, two accepted papers, three accepted conference summaries.

Learning outcome:

- During this first year of the project more than 100 students benefited from these teaching experiments. Among them are students of three departments of the UR, including 25 freshmen, MCC, RIT as well as students and teachers from Brighton High School.

- Using questionnaires on photon quantum mechanics showed that 63% of OPT 223 students (UR) answered correctly 90% of questions, 60% of MCC students answered correctly 80% of questions and 60% of freshmen of OPT 101 (UR) participating in research answered correctly 70% of questions.
- Students' mastery in photon-counting instrumentation of 4-credit hour course with 15-hour labs is shown in that 60% 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. All students answered correctly 90% of questions.

Community building outcome:

- Three Rochester educational institutions (UR, MCC, RIT) collaborate and share their experience on improvement of student learning at these *diverse* educational institutions in quantum mechanics and modern physics.
- We interacted with investigators of other universities and counties working on similar or related approaches: Galvez (Colgate University), Beck (Whitman College), Bentley (Adelphi University), Noel (Bryn Mawr College).
- Teaching experiments were shown to Capasso (Harvard University), Aspect (Institute d"Optique, France), Belyakov (Landau Institute for Theoretical Physics (Russia), and other visitors of the Institute of Optics.
- Our website of Quantum Optics and Quantum Information Laboratory has already more than 1,700 visitors. Some people contact us directly by e-mails.
- Prof. Stroud delivered invited lecture in Pennsylvania, Lukishova was invited to deliver her lecture in Oklahoma this September.

Below is a more detailed description of some above-mentioned findings. This first year of the project was devoted to developing of quantum optics teaching experiments at RIT using the experience of UR, developing and teaching 3 hour versions of four teaching labs ("mini-labs") for UR and MCC, preparing lecture materials for the labs, teaching the 4-credit hour course, lecture-demonstrations to students of different experience including freshmen and high-school students, work on a mobile single-photon source device, starting data collection for evaluation of students' knowledge and the first evaluation of the project by the internal evaluator.

1. DESCRIPTION OF TEACHING EXPERIMENTS WITH EXPERIMENTAL RESULTS PERFORMED BY STUDENTS OF DIFFERENT LEVELS

Lab. 1. Entanglement and Bell's inequalities

The schematic of the teaching experiment on *polarization-entangled* photons and Bell's inequalities is shown in the Figure 1, left. We used P. Kwiat approach [*Phys. Rev A*. **60**, R773 (1999)]. Light from the laser passes through a pair of type I 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 A and B). These two APDs are located on two diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization (*H* or *V*). A 45^o polarized pump photon can be downconverted in either crystal, producing a polarization entangled pair of photons:

$|H\rangle + |V\rangle \rightarrow |V_s V_i\rangle + \exp(i\Delta)|H_s H_i\rangle$. Quartz plate rotation compensates phase Δ introduced by the crystals. Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, right (obtained by the students of 3-hour-lab version) 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 α of the linear polarizer A varies at two different fixed angles β of the polarizer B. Calculation of Bell's inequality in the Clauser-Horn-Shimony-Holt form shows its violation (S > 2).

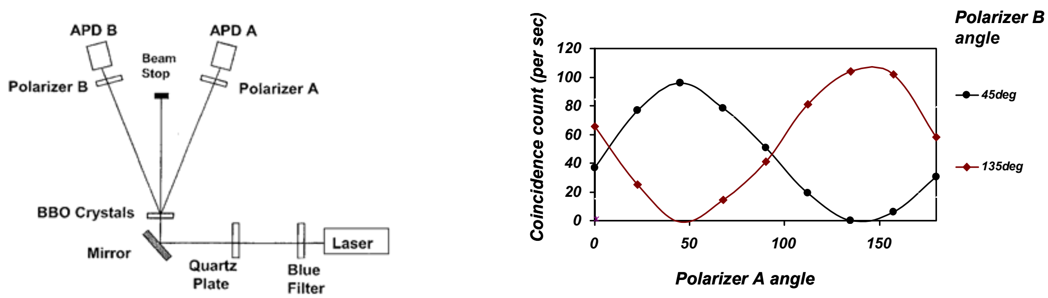


Figure 1. Entanglement and Bell's inequalities lab: left – schematics of the experiment (interference filters transmitted only downconverted light 727.6 nm are placed in front of each detector); right – coincidence count dependence on relative polarizer angle in front of detectors A and B. High fringe visibility (greater than 0.71) indicates Bell's inequality violation and entanglement.

UR has two experimental setups located in different rooms with different lasers and different BBO crystal sets. One setup (Figure 2) was used for teaching experiments, another (Figure 3) – for modeling of the RIT version of this lab. For UR teaching labs we use an 100 mW, 363.8 nm, cw argon ion laser donated by Spectra Physics division of Newport Corporation. The results on this setup are very reproducible and we used it for quick demonstration of photon entanglement during only 2-3 hours of "mini-lab" for several groups of students of different levels (UR and MCC).

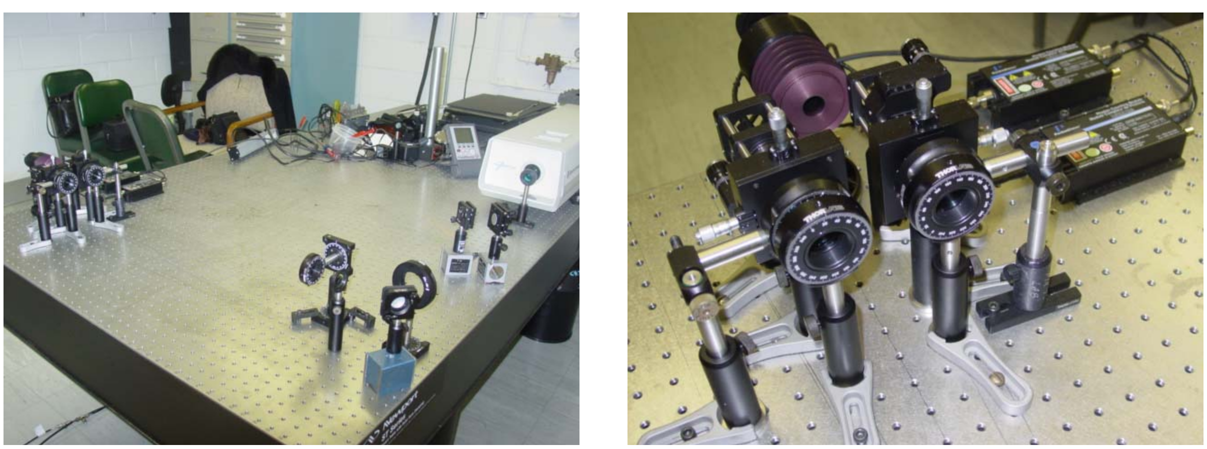


Figure 2. Entanglement lab setup with an argon ion laser (left) and its entangled photon registration module (right).

This setup also permits students to observe and prepare video files of the cone of downconverted photons using a low-light level EM-CCD camera.

The second setup with 10 mW, 406 nm excitation (diode laser) is shown in Figure 3. This setup was described in papers of D. Dehlinger and M.W. Mitchell [*Am. J. Phys.*, **70**, 898 and 903 (2002)]. Jodoin (RIT) during his sabbatical at the UR and Lukishova worked on developing an easier method of alignment of this setup as well as on the use of a cheap computer board for coincidence count measurements.

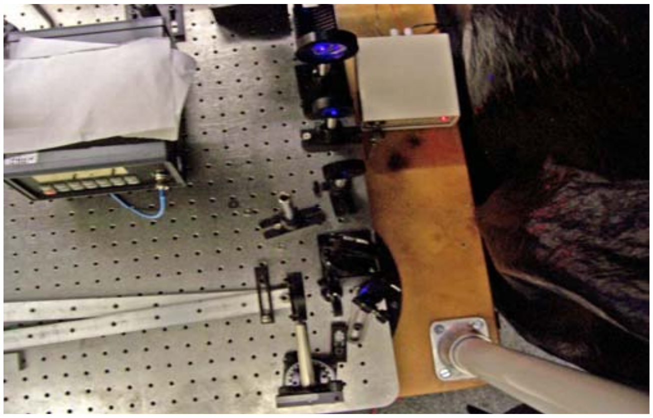
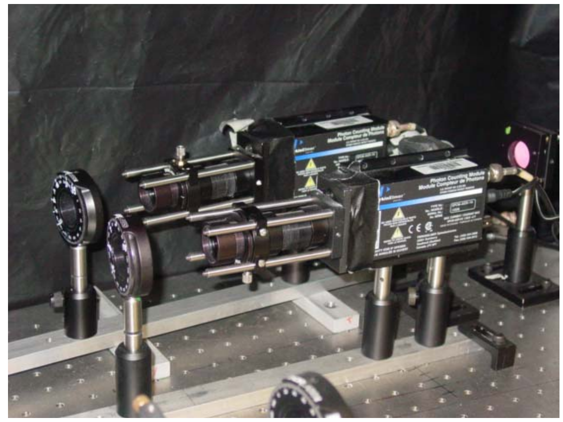
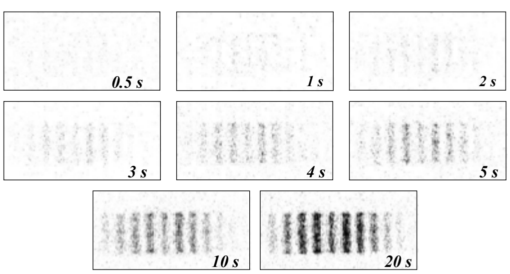



Figure 3. Part of entanglement lab setup with a diode laser excitation (left) (APDs and polarizers are not shown) and its entangled photon registration module with APDs and polarizers (right).

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 are made using a He-Ne laser beam, attenuated to the single photon level and an EM-CCD camera (Figure 4, left). Mach-Zehnder interferometer (Figure 4, right) is used for the demonstration of a single-photon interference after removing "which-way" information (identification of the path). Figure 5 shows photographs of experimental setup (left) and one of three groups of Monroe Community College students carrying out this experiment.



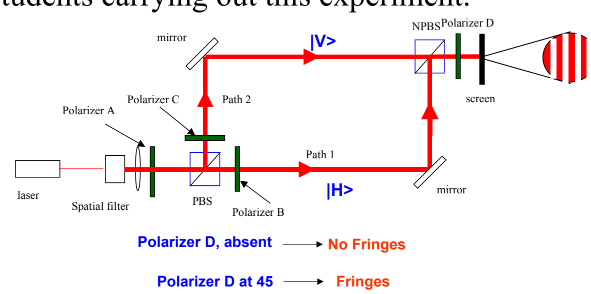


Figure 4, Left: Single-photon interference using Young's double-slit at different exposure time. Right: Mach-Zehnder interferometer schematics for "which-way experiment

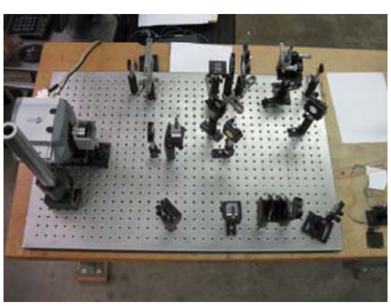



Figure 5. Photograph of single-photon interference setup with low-light level EM-CCD-camera (left); group of MCC students (right) carrying out this experiment.

Lab 3. Single photon source I: Confocal microscope imaging of single-emitter fluorescence
This Lab and the next, Lab 4, are devoted to a single-photon source (SPS) with photons separated in time (antibunching). To produce single photons, excited laser beam should be focused on a single emitter which produces single photon at a time. SPS is the key hardware element of quantum cryptography. At the same time methods and instrumentation of confocal fluorescence microscopy are widely used in nanotechnology, biology and biomedicine.

Laser excitation at 532-nm (8 ps pulse duration, 76 MHz pulse repetition rate) as well as at 514 nm (cw) was used for confocal microscope single-emitter fluorescence imaging in the teaching labs (Figure 6). Colloidal semiconductor quantum dots and single color-centers in nanodiamonds were used as single emitters.

Students enrolled in the laboratory course also participated in research. They carried out imaging of single emitter fluorescence in photonic bandgap cholesteric liquid crystal hosts and photon antibunching measurements, observed "blinking" of quantum dots using raster scan or wide-field microscopy with EM-CCD camera.

Figure 6. Left: Photograph of a confocal fluorescence microscope for SPS applications; Right: Freshmen work on 12-hour research project of "Optics for information age" course (Fall 2009).

Lab. 4. Single Photon Source II: Hanbury Brown and Twiss setup. Fluorescence antibunching
Hanbury Brown and Twiss interferometer for fluorescence antibunching measurements consists of a nonpolarizing 50:50 beamsplitter forming two arms. This set up is placed at one of the output ports of a confocal fluorescence microscope. The time interval τ between two consecutively detected photons in separate arms is measured by a 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. 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 shows some results of freshmen group of their 12-hour research project (course "Optics in information age"): left – time traces of count rate on one of APD detectors showing "blinking" of CdSeTe colloidal quantum dots, right – fluorescence antibunching curve (CdSeTe quantum dot) with a dip at zero interphoton time (from freshmen group presentation).

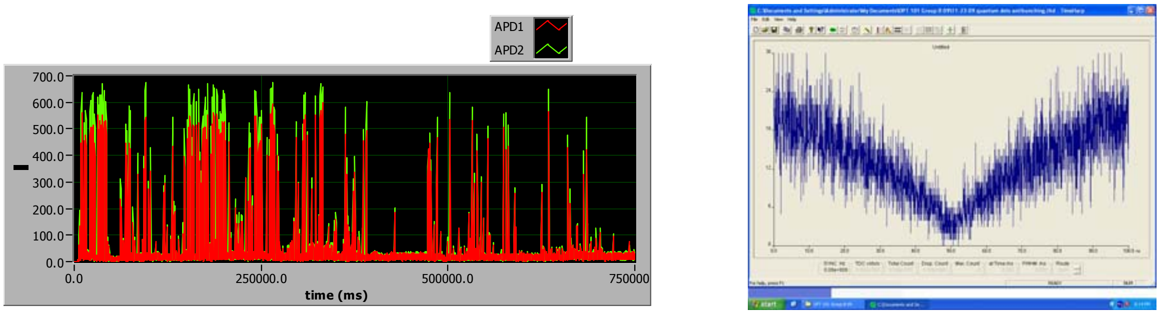


Figure 7. Some freshmen group results: left – time traces of photon count showing “blinking” of CdSeTe colloidal quantum dots; right – fluorescence antibunching curve (CdSeTe colloidal quantum dot).

Single Photon Source III: Mobile source of single photons based on color centers in nanodiamonds

During this first year of the project we accomplished the main work on preparation of a mobile SPS with excitation of a stable, unbleachable single emitter (single color center in nanodiamond) through the optical fiber. This SPS can be easy transported to other Universities.

Both freshmen of 12-hour research project and students enrolled with 4-credit hour course were able to obtain imaging and fluorescence antibunching from single color centers in nanodiamonds. Figure 8, left shows image of single NV-color center fluorescence using confocal fluorescence microscope. Figure 8, right shows histogram-indicated fluorescence antibunching of this single emitter.

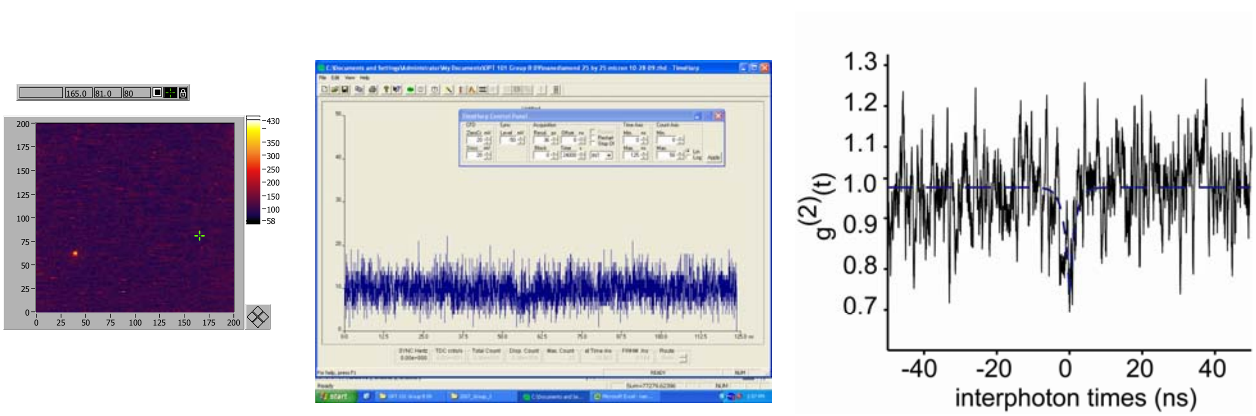


Figure 8. Preparation of a compact transportable SPS based on color centers in nanodiamonds in cholesteric liquid crystal chiral photonic bandgap host: Left and center – Freshmen research results (Confocal microscope fluorescence image of color centers and histogram of coincidence counts from color center showing dip at zero interphoton time (fluorescence antibunching). Right figure shows color center fluorescence antibunching in cholesteric host of Lukishova’s research group.

2. PROVIDED OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

More than 100 students benefited from the project during the first year of funding. The groups of trained students with different level are listed below:

(1) 10 students (two groups) of freshmen OPT 101 course "Optics in the Information Age" (Knox) carried out 12 hour research projects on single photon source and single photon interference (Lukishova).

Figure 9. One of two research groups of freshmen course OPT 101 at the single photon interference lab.

(2) 25 students (four groups) of freshmen OPT 101 course "Optics in the Information Age" (Knox) participated in lecture-demonstrations of four teaching experiments in quantum optics (Lukishova). This demonstration provided students a laboratory experience with the concepts that they studied on the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.)

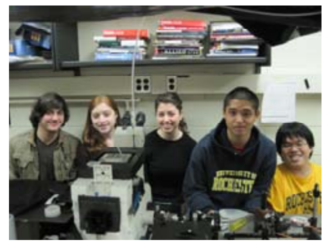


Figure 10. One group of four groups of freshmen course OPT 101 during lecture demonstration of quantum optics experiments.

(3) 17 students (four groups) of OPT 223 course "Quantum mechanics of Optical Materials and Devices" (Stroud), carried out two 3-hour labs (entanglement and Bell's inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

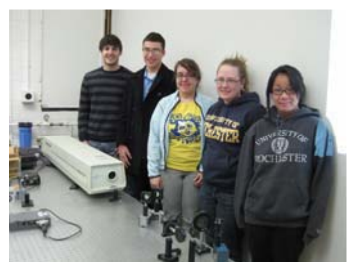


Figure 11. One of four groups of OPT 223 students at entanglement and Bell's inequalities lab.

(4) 14 students of Monroe Community College of Modern Physics course (D'Alessandris) carried out two three hour labs (D'Alessandris, Lukishova) at the University of Rochester (entanglement and Bell's inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

Figure 12. One of three groups of Monroe Community College students at entanglement and Bell's inequalities lab.

(5) 7 students of four-credit hour course OPT253 "Quantum Optics and Quantum Information Laboratory" A

teaching assistant of this course was also trained.

(6) 35 students (3 groups) and their teachers from Brighton high school participated in lecture-demonstrations of quantum optics laboratory (Knox, Lukishova).

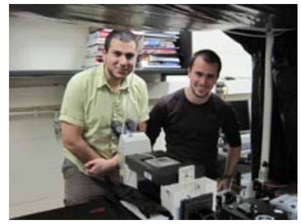


Figure 13. Two undergraduate students of OPT 253 course at the single photon source lab.

In addition, three graduate and one undergraduate student carried out research projects using different modules of this teaching laboratory facility.

3. OUTREACH ACTIVITIES

1. See (6) of Section 2 (Lecture-demonstrations of quantum optics laboratory to Brighton high-school students and teachers (Knox, Lukishova);
2. Stroud delivered lectures on "Quantum weirdness" in several Universities (Undergraduate colloquium - University of Puget Sound - Sept 2009; Public Lecture - Pacific Lutheran University - Sept 2009; Stookey Award Lecture - Corning, Inc. - Oct 2009; Keynote Address - Annual meeting of New York Science, Engineering and Technology Association; Corning Community College, October 2009; Welcoming Address - Symposium on Quantum Engineering - University of Rochester, Oct. 2009).
3. Lukishova is invited this September to the University of Oklahoma (Tulsa) to give a talk as well as to discuss challenges in organizing quantum optics laboratory.

4. 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.

We evaluated four groups of students: (1) UR students who took 15-hour version of the OPT 253 labs (5 from total 7 students participated in this evaluation); (2) UR students who took three-hour lab versions (OPT 223) (14 students from total 17 participated in this evaluation); (3) Monroe Community College students (three-hour versions of the labs) (13 and 14 students from total 14 students participated in this evaluation); (4) UR freshmen of OPT 101 course 12-hour research projects (10 students from total 25 students participated in this evaluation).

Formative evaluation was carried out by 5 students enrolled in the laboratory course taught by Lukishova (OPT 253). 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 indicating the success of the course. At the end of "Project Activities and Findings" section we attached written students' opinion about this course which was sent us by the Dean's office).

Summative evaluation was accomplished by two ways: (1) using different questionnaires (without grading) and (2) using the grades for each lab. Teaching assistants helped in summative evaluation. Histogram in Figure 14 shows percent of correct answers to seven questions of Lab 1 for OPT 223 students after lab completion.

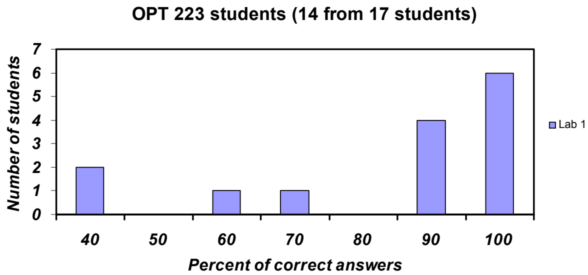


Figure 14. Histogram of evaluation of student learning for OPT 223 labs.

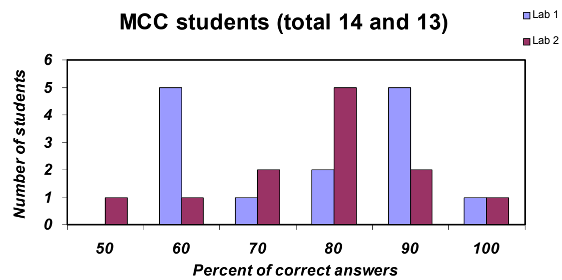


Figure 15. Histograms of evaluation of student learning for Monroe Community College students.

Figure 15 shows the same histograms (Labs 1 and 2) for Monroe Community College students. Two laboratory activities (single photon interference and entanglement) from the Quantum Optics and Quantum Information Laboratory course at the University of Rochester (OPT 253) were adapted into a three-hour format appropriate for sophomore level Modern Physics students at Monroe Community College (PHY 262). 14 students enrolled in Modern Physics at MCC conducted these experiments at UR in groups of 4 or 5. MCC students participated in a brief tutorial on the theoretical issues involved in the experiments before visiting UR and completed a conceptual evaluation at the conclusion of each experiment. Students are also informally debriefed on the experience upon their return to MCC.

Figure 16 shows the result of evaluation of learning for freshmen of OPT101.

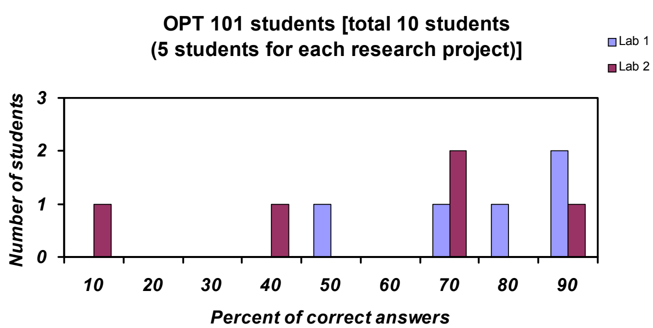


Figure 16. Histogram of evaluation of freshmen learning (OPT 101 course research projects).

Questionnaire with 32 questions on photon quantum mechanics of OPT 253 course showed that percent of correct answers of all students was greater than 90%. Table 1 shows each student performance.

95.6
96.6
97.2
91.2
93

Table 1. Percent of correct answers of each of 5 students participated in evaluation of their knowledge for OPT 253 course Quantum Optics and Quantum Information laboratory (Lukishova).

Students' mastery in photon-counting instrumentation of OPT 253 course showed that 60% of students received total scores of "A" and the rest of students received total scores of "A-". (Students were permitted to rewrite their reports). The grades were based on students' capability of carrying out the experiments, writing the reports, delivering oral presentations and answering questions during Mid Term and Final Exams.

5. PUBLICATIONS AND PRESENTATIONS (first year of the project)

5.1. Journal publications and periodically published conference proceedings

1. S.G. Lukishova, L.J. Bissell, C.R. Stroud, and R.W. Boyd, "Room-temperature single photon sources with definite circular and linear polarizations", Optics and Spectroscopy, Springer, 108, 452 (2010).
2. L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr., and R.W. Boyd, "Chiral photonic bandgap microcavities doped with single colloidal semiconductor quantum dots", Proceedings SPIE, 2010, accepted.
3. L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr., "Room-temperature single photon sources with definite circular and linear polarizations based on single-emitter fluorescence in liquid crystal hosts", Proceed. SPIE, 2010, accepted.
4. M.A. Landau and C. R. Stroud, Jr., "Calculation of the convex roof for an open entangled harmonic oscillator system", Phys. Rev. A 81, 052304 (2010)
5. H. Nihira and C. R. Stroud, Jr., "Steady-state two-atom entanglement in a pumped cavity", Phys. Rev. A 80, 042329 (2009)

5.2. One-time publications in conference proceedings

6. L. Bissell (Advisors: C.R. Stroud and S.G. Lukishova), "Room-Temperature, On-Demand Single-Photon Sources", Ph.D Thesis Proposal, The Institute of Optics, University of Rochester, 2010, submitted.
7. L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr, and R.W. Boyd, "Room-temperature single photon sources with definite circular and linear polarizations based on single-emitter fluorescence in liquid crystal hosts", International Conference on Coherent and Nonlinear Optics, Kazan', Russia, Nanophotonics and Plasmonics, Kazan', Russia, 23-26 August 2010.

8. L.J. Bissell, S.G. Lukishova, A.W. Schmid, M.A. Hahn, C.M. Evans, T.D. Krauss, C.R. Stroud, Jr, and R.W. Boyd, “Chiral photonic bandgap microcavities doped with single colloidal semiconductor quantum dots”, International Conference on Coherent and Nonlinear Optics, Kazan', Russia, Nanophotonics and Plasmonics, Kazan', Russia, 23-26 August 2010.

5.3. Website:

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

Comments Report for Fall 2009, OPT 253 QUANTUM OPTICS LABORATORY Section 72702

Instructor: LUKISHOVA, SVETLANA (Primary)

Instructor	Avg eval score	Text Responses
		Question: Comments:
	> 75%	The concepts in this course were difficult to understand. A lot of research was done during my lab report write ups.
	> 75%	I worked hard with this course. Before the lab, I read the manual. In the experiment, I carefully recorded each steps, and discussed with the Professor and classmates, and quite involved in the lab. After the lab, I took the lab report carefully.
		Question: Comments:
	> 75%	I walked into the course with no knowledge of Quantum Optics whatsoever. Now that this is
	> 75%	I have no previous knowledge of quantum mechanics, I learned a lot from this course, and I believe it will help me next semester when I take quantum optics.
	> 75%	Quantum Optics is new area for me. I learned the theory of Quantum Mechanics before. While, this Quantum Optics Lab gives me direct experiences of quantum. We can make quantum photons with our own hands, and can observe their quantum characters. We also work with some advanced instruments.
		Question: Comments:
	> 75%	Doctor was able to tell us clearly what the point of everything we were doing was, whether it be in the manual, syllabus or discussions.
	> 75%	N/A
	> 75%	Very good.
		Question: Comments:
	> 75%	To know and understand the lab manuals was imperative to understanding what had to be done during each lab session and a proper right-up!
	> 75%	The readings provided in the course, like the lab manual was crucial to performing well in the lab.
	> 75%	In this course, the most important is taking part in the experiment. And for me, the second important is reading. To understand the thoery, and to know how to do the experiment, I need to read papers and manuals. It is very important and I learned a lots in reading.
		Question: Comments:
	> 75%	Any extra reading pertained exactly to what we were trying to accomplish in the labs. And they were very informative and interesting!
	> 75%	There were lab reports, an essay, a presentation, a midterm, and a final. They all supported the course objectives.
	> 75%	The assignments and exams are mostly about the experiment process and theory. So as long as you take part in the experiments and undertand every steps and results, the assigenments and exams are not very difficult.
		Question: Comments:
	> 75%	Starting from scratch and working all the way up to a full understanding is exactly what any class should do. This was by far the best class that has ever actually been just that: a class - a learning experience to gain knowledge and better ones education and understanding. This may have even benefited more since it was a lab course. I feel like I learned more "material" working in the lab every day than I have in lectures and homeworks with other classes. I can't write enough of a glowing review.
	> 75%	Very beneficial course. Working with a very smart instructor who knows her quantum. Worked with equipment that many people have the chance to work with.
	> 75%	I think it worths the time and efforts.
		Question: What are the major strengths of this course?

	> 75%	Working with cutting edge material, doing true research as an undergraduate, learning lab protocol. I believe that my write-ups for future anything will be greatly improved after having gone through this course.
	> 75%	State of the art equipment, caring and very knowledgeable professor.
	> 75%	It gives us the first-hand experiences of quantum optics.
		Question: What are the major weaknesses of this course? Please make suggestions for improvement.
	> 75%	I feel like it needs to get bigger! While the small group was fantastic, I wish that more people would become involved so that it gains the momentum and attention it deserves!
	> 75%	Big groups is definitely a negative in the lab. I understand the professor had to be with us in the lab most of the time because of the research equipment, but without here presence, the TA made a very good job ensuring the students' and equipments' safety. Smaller groups would definitely help, more hands on time for each person. There 5 students in this course and we all did the same presentation, with the same experimental data. In the future, I believe it could be more beneficial if each student focuses on one lab, or make the presentations in Groups. Lastly, Assign the essay earlier in the semester. Last week of the semester just for this class, there was a final, presentation, essay, and lab 3 and 4 due.
		Question: Comments:
LUKISHOVA	> 75%	There was never a time when she was unable to answer a question or approach it in a way that would make sense. Her labs were built so that we learned as we went, and when we fully understood how to handle the experiment, we were able to do it practically all by ourselves. In other words: we were taught, we learned it, and we excelled. Doctor Lukishova had an extreme impact on that happening.
LUKISHOVA	> 75%	Professor Lukishova took part in all the experiments with students. First, she would ask how much do we know about the exam, and then she show us how to do, and let us do it ourselves one by one. Every students are encorged to do the experiments and ask questiones. Besides the manual, she also gave lectures, which cover wider information about the lab which are very helpful.
		Question: Comments:
LUKISHOVA	> 75%	I had a very vague understanding of what all the topics we touched on were, and even less of how it could be at all practical. Now, I can speak better on each of them then any of my colleagues. Not to mention, I have always had an interest in what the next "big thing" has been, and this whole course is based on what IS going to be the future of practically all technology. It was very eye-opening and exciting to work on such material. I hope I get to do it again in the future.
LUKISHOVA	> 75%	She made it look easy.
LUKISHOVA	> 75%	It is very free in this class. Whenever you have questions, we can discuss with the Professor. And no intense pressure about assignments and exam, because we usually have enough time, and we can improve them. So it makes me more relax to do it, and be willing to pay more efforts to get a higher score.
		Question: Comments:
LUKISHOVA	> 75%	Thanks again. Not only was it fun and entertaining most of the time, but the experience I have gained really excites me. I truly believe I have finally learned something from taking a course.
LUKISHOVA	> 75%	I greatly recommand this course for students who are interested in quantum and quantum optics.
		Question: Comments:
LUKISHOVA	> 75%	She says it best: we are students, we are learning, don't be afraid to get anything wrong, you must try and learn. I wish every professor / teacher / mentor, whatEVER had this mentality towards passing knowledge on. It was incredibly easy to learn everything from Doctor Lukishova because she understood that we were, well, just students and just gaining the abilities to discern what is actually going on. She cared an almost ridiculous amount about how well we took on the material. It was awesome to have a teacher really be there every step of the way and make sure that we got every inch of material.
LUKISHOVA	> 75%	Meetings were easy to set, and will meet with you whenever you need. She is a very caring instructor, she insures that everyone understands the material before moving on.
LUKISHOVA	> 75%	My classmates and I always discussed with Professor Lukishova. She often inspired students to ask questions.
		Question: What are the major strengths of this instructor?

LUKISHOVA	> 75%	She cared extremely about our learning, not about our passing the class, our absorbing the material that she put in front of us. It was inspiring to be around someone that had such care for their work that they wanted to teach us so fully. Loved it! Thank you so much.
LUKISHOVA	> 75%	knowledgeable, caring, fair.
LUKISHOVA	> 75%	Professor Lukishova is very professional in this research area. Furthermore, she knows how to teach well and she understands students very much.
		Question: What are the major weaknesses of this instructor? Please make suggestions for improvement.
LUKISHOVA	> 75%	To cite a weakness would be a flaw in itself. I had NO problems all semester and find it hard to even fathom that someone would have a problem with how she conducted everything.
LUKISHOVA	> 75%	organization, especially with due dates.
		Question: If there are any other further comments you would like to make about this course, please do so in the space provided below.
LUKISHOVA	> 75%	I am going to parade the need for this course to be taken around to everyone. Every underclassmen I know better be signed up. I would be very upset if this course went unnoticed for any longer!

Distribution Report for Fall 2009, OPT 253 QUANTUM OPTICS LABORATORY Section 72702

Instructor: LUKISHOVA, SVETLANA (Primary)

	Question Text	N	Top Two	Avg	Major	Elective	Other	Uncertain			
1	Status of course	4			100%	0%	0%	0%			
					Fresh	Soph	Junior	Senior	Graduate	No Matric	Other
2	Class year	4			0%	0%	0%	75%	25%	0%	0%
					Ful engaged	Most Engaged	Average	Par Engaged	Min Engaged		
3	Involvement	4	100%	5	100%	0%	0%	0%	0%		
					G Increase	Increase	Ave	Min inc	Not inc		
4	Student increase knowledge	4	100%	5	100%	0%	0%	0%	0%		
					Profess		OK		Not Profess		
6	Rate yourself in course	4	100%	5	100%	0%	0%	0%	0%		
					Extr Well	V Well	Well	N Well	N/A		
8	Syllabus describe course content	4	100%	4.8	75%	25%	0%	0%	0%		
					VI	SI	NI	NA			
10	Readings were important in my learning of the course	4	100%	5	100%	0%	0%	0%			
					Extr Well	V Well	Well	N Well	N/A		
12	Did assignments and exams support objectives	4	100%	4.8	75%	25%	0%	0%	0%		
					Excellent	V Good	Ave	NV Good	VP		
16	Overall course rating	4	100%	5	100%	0%	0%	0%	0%		
					VRespon	MRespon	Aver	MRespon	URespon		
18	Responsiveness (LUKISHOVA)	4	100%	5	100%	0%	0%	0%	0%		
					VEffect	Effect	Aver	Min Effect	Ineffect		
20	Effectiveness (LUKISHOVA)	4	100%	5	100%	0%	0%	0%	0%		
					Str Agree	SW Agree	Neutral	SW Dis	Str Dis		
22	Have a stronger interest in this subject because of this instructor (LUKISHOVA)	4	100%	4.8	75%	25%	0%	0%	0%		
					Excellent				Poor		
26	Overall instructor rating (LUKISHOVA)	4	100%	5	100%	0%	0%	0%	0%		