Principal Investigator: Stroud, Carlos R.
Organization: University of Rochester
Title:
MRI: Development of single photon generation & characterization unit

Project Participants

Senior Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Worked for more than 160 Hours:</th>
<th>Contribution to Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroud, Carlos</td>
<td>Yes</td>
<td>Carlos R. Stroud, Jr. is the project's Principal Investigator. He is one of the main persons who constructed the instrument. He selected students for this project and supervised their research on building both electronic and optical parts of the instrument. He wrote papers and presented the results at conferences.</td>
</tr>
<tr>
<td>Novotny, Lukas</td>
<td>Yes</td>
<td>Lucas Novotny is a co-Principal Investigator of this project. His group wrote the imaging code based on LabView. He was one of the main persons who participate in construction of the instrument.</td>
</tr>
<tr>
<td>Lukishova, Svetlana</td>
<td>Yes</td>
<td>Svetlana Lukishova is a co-Principal Investigator of the project. She is one of the main persons who constructed the new instrument. She supervised students on building this instrument, sample preparation, single-molecule fluorescence microscopy, photon statistics measurements. In addition, she participated in educational part of the project preparing an inside University proposal of using both the instrument and its modules as a part of quantum optics/quantum information teaching laboratory for seniors of three departments. She wrote papers and presented the results at conferences. Dr. Svetlana Lukishova was awarded by the University of Rochester Kauffman Foundation Initiative for her Quantum Optics and Quantum Information Teaching Laboratory Course consisting of four experiments prepared during the Summer of 2006. All these experiments contain different modules of the single-photon generation and characterization unit. Both graduate and undergraduate students from two University departments took this course from September 2006.</td>
</tr>
<tr>
<td>Sobolewski, Roman</td>
<td>Yes</td>
<td>Roman Sobolewski is a co-Principal Investigator of the project. He and his group have designed, implemented, and tested a novel, two-channel single-photon receiver for telecommunication wavelength, based on two fiber-coupled NbN superconducting single-photon detectors. Prof. Sobolewski has also worked on the physics of the single photon detection mechanism in nanostructured superconducting stripes, studying the dynamics of the hotspot formation, the photoresponse speed, and the origin of dark counts in NbN superconducting single-photon detectors. He wrote papers and presented the results at conferences.</td>
</tr>
<tr>
<td>Knox, Wayne</td>
<td>Yes</td>
<td>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. A lecture demonstration of single-photon interference was prepared for his course 'Optics in the Information Age'.</td>
</tr>
</tbody>
</table>

Post-doc
Graduate Student

Name: Bissell, Luke

Worked for more than 160 Hours: Yes

Contribution to Project:
Graduate student Luke Bissell worked on this project the whole Summer and continues to work at the present time under the supervision of both Prof. Stroud and Dr. Lukishova. He made significant contribution in alignment of the optical part of the single photon source including confocal microscope and the Hanbury Brown and Twiss setup for photon statistics measurements. He submitted a Summer report on his activity.

Luke Bissell was awarded in 2006 by SMART four-year-Fellowship from US Airforce for his graduate studies in the field of quantum information.

Name: Pearlman, Aaron

Worked for more than 160 Hours: Yes

Contribution to Project:
Aaron Pearlman is a graduate student supervised by Prof. Sobolewski. He tested NbN superconducting single-photon detectors using the single-photon statistics measurement module of the new instrument.

A. Pearlman defended his PhD thesis entitled: 'Ultrafast Superconducting Single-Photon Detectors for Quantum Communications.' Prof. Sobolewski was his advisor.

Name: Cross, Allen

Worked for more than 160 Hours: Yes

Contribution to Project:
Allen Cross is a graduate student supervised by Prof. Sobolewski. He tested NbN superconducting single-photon detectors using the photon-statistics measurement module of the new instrument.

Name: Rako, Stephen

Worked for more than 160 Hours: Yes

Contribution to Project:
Stephen Rako is a Master graduate student of Prof. Sobolewski. He is working on the project for approximately three months. He made simulations of the results of testing of NbN single-photon detectors.

Name: Kitaygorsky, Jennifer

Worked for more than 160 Hours: Yes

Contribution to Project:
Jennifer Kitaygorsky is graduate student of Prof. Sobolewsky. The title for her PhD proposal is 'Dark counts in NbN superconducting single photon detectors and nanobridges.' She study dark counts, observed as transient voltage pulses, in the current-biased NbN superconducting single-photon detectors (SSPDs), as well as in ultrathin (3.5-10 nm), sub-micrometer-width (100-500 nm) two-dimensional (2-D) NbN bridges of various length (0.001-0.5 mm) and width. Dark counts were measured while devices were completely isolated (shielded by a metallic enclosure) from the outside world, in a temperature range between 60 mK and 9 K. Dark counting rate was also measured as a function of bias current for the range of temperatures listed above. These measurements will help to shed some new light on the physics of dark counts, and, from the applied point of view, on the intrinsic performance of SSPDs.

Name: Pan, Dong

Worked for more than 160 Hours: Yes

Contribution to Project:
Graduate student Dong Pan of Prof. Sobolewski prepared Ph.D proposal with approximate title 'Fiber coupled single photon detector for quantum cryptography and the photon response of NiCu/Nb bilayer.' He tested the time delay dependence of system quantum efficiency (SQE) of fiber coupled superconducting single-photon detector (SSPD) based on NbN nanostructures. He also measured the spectral dependence of fiber coupled SSPDs and proved the tradeoff between the counting rate and active area, which relate to the kinetic inductance of the devices. Both single mode and multimode fiber coupled receivers showed similar exponential trends of SQE versus wavelength.
Undergraduate Student

Name: Schrauth, Sam

Worked for more than 160 Hours: Yes

Contribution to Project:
Sam Schrauth, undergraduate student was supervised by both Prof. Stroud and Dr. Lukishova. He contributed to the electronic part of the new instrument. He worked on imaging software problems jointly with Prof. Novotny’s group as well. He submitted a Report of his work.

Sam Schrauth accomplished his undergraduate research project on a single-photon source setup.

Name: White, Sean

Worked for more than 160 Hours: Yes

Contribution to Project:
Sean White worked on this project as a participant of the University of Rochester Summer Program Research Experience for Undergraduate, supported by the NSF. He worked on single-colloidal quantum dots imaging in cholesteric liquid crystal host and antibunching correlation measurements.

Name: Savidis, Nickolaos

Worked for more than 160 Hours: Yes

Contribution to Project:
Nicholaos Savidis worked on this project two Summer months as a participant of the University of Rochester Program Research Experience for Undergraduates supported by the NSF. He worked with a low-light EM CCD camera to record single-photon interference in Mach-Zehnder interferometer. He measured coincidence counts from two single-photon counting avalanche photodiode modules, he prepared chiral photonic bandgap planar-aligned liquid crystal layers doped with single dye-molecules and/or colloidal semiconductor quantum dots. He made contribution to the educational part of this project as well.

Technician, Programmer

Name: Adamson, Per

Worked for more than 160 Hours: Yes

Contribution to Project:
Per Adamson spent significant part of his time on construction and building of the instrument. He also one of the main people involved in educational activity and preparation of new teaching laboratory courses.

Other Participant

Research Experience for Undergraduates

Organizational Partners

Cornerstone Research Group, Inc
Cornerstone Research Group (Dayton, OH) made in-kind support for the project, providing both glassy cholesteric and nematic liquid crystal materials for the samples. These new materials with low fluorescence background were synthesized by this company which provided them to the Institute of Optics at no cost, in exchange for research experiments on purity of synthesized materials. A Report was presented to the company on single-molecule fluorescence in provided materials.

Other Collaborators or Contacts

(1) We have a 'no cost' collaboration with the Laboratory for Laser Energetics, University of Rochester on sample preparation and characterization. Laboratory for Laser Energetics provided both liquid crystal clean room facility for sample preparation/alignment (K. Marshall) and nanometrology laboratory alpha-SNOM device for single-molecule fluorescence experiments (Dr. Schmid).
(2) For some experiments we used materials synthesized by Prof. Chen's group, Department of Chemical Engineering, University of Rochester.

(3) Dr. A. Lieb, University of Basel (Switzerland) contributed to fluorescence imaging software.

(4) Prof. J. Dowling (Louisiana State University) contributed to our understanding of spontaneous emission in photonic bandgap materials.

(5) BBN technology which is building the world's first Quantum Key Distribution network received a report about our progress on a single-photon source instrument.

(6) Inside the University of Rochester we collaborate with both Prof. R.W. Boyd (the Institute of Optics) and Prof. S.-H. Chen (Department of Chemical Engineering), on lasing in photonic bandgap cholesteric liquid crystal layers using special fluorescent dyes.

(7) Dr. Lukishova visited Prof. Menon (Queens College of CUNY, New York) for a collaboration on colloidal quantum dot fluorescence in photonic bandgap structures. Prof. Menon is planning to prepare for Dr. Lukishova organic 1-D photonic bandgap structures doped with single quantum dots.

8) Prof. Chen's group (Department of Chemical Engineering, University of Rochester) synthesized glassy cholesteric liquid crystal materials. Graduate student Simon K. Wei prepared 1-D photonic bandgap structures from these materials doped with colloidal quantum dots.

8) We collaborated with Prof. Chen's (Department of Chemical Engineering, University of Rochester) and Prof. Boyd's (the Institute of Optics, University of Rochester) groups on optimal conditions of lasing in cholesteric liquid crystal photonic bandgap structures. The same structures were used for spontaneous emission enhancement in our single-photon source unit with the same optimal position of emitter fluorescence maximum on a photonic band edge of the structure.

(9) Prof. T. Krauss group (Department of Chemistry, University of Rochester) synthesized colloidal semiconductor CdTe and PbSe quantum dots with maximum fluorescence at 580, 800 and 1,500 nm.

(11) Prof. V. Menon's group (Queens College, CUNY, New York) prepared for us 1-D organic nonchiral photonic bandgap structures doped with colloidal CdSe quantum dots with fluorescence maximum at 620 nm. We used these structures in our single-photon source setup.

(12) In June 2007 Dr. Lukishova visited collaborative company BBN Technologies and delivered a talk about this projects' results on a single photon source unit. The possibility of using of this unit in current quantum optical network of BBN technologies was discussed.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
SEE ALSO ATTACHED FINAL REPORT 2004-2007 ACTIVITIES AND FINDING FILE WITH MORE DETAILS AND ILLUSTRATIONS:

Project goal: This three-year-project's goal is the development of a new instrument (single photon generation and characterization unit) satisfying the needs of several University of Rochester departments working in the field of quantum optics/quantum information, single photon detection/measurements, nanotechnology, fluorescence spectroscopy and microscopy. This instrument, a prototype of a key hardware for practical, absolutely secure quantum communications, is based on fluorescence of single emitters embedded in a host material. This project was carried out in contact with BBN Technologies, company which built first quantum communication network in Boston area.

The project also includes the development of samples with single emitters as well, for a room-temperature alternative to cryogenic-temperature single photon sources. For this purpose liquid crystal hosts with photonic bandgaps doped with single dye molecules or semiconductor colloidal quantum dots were developed.
The liquid crystal hosts which can exist both as monomers (fluid media) and oligomers/polymer serve two purposes. Nematic liquid crystals align the dye molecules along a definite axis. Such aligned molecules would normally emit in a dipole pattern which is a big improvement over the more common situation in which the molecular axes, and thus the dipole patterns, are randomly oriented in space. The chiral nematic (cholesteric) liquid crystals further improve the situation by providing a photonic crystal environment into which the molecules will emit. This environment is provided by supplying a torque to the medium as it is being laid down. The liquid crystals are dichroic, and this torque causes the principal axis of the index of refraction to rotate periodically about an axis perpendicular to the thin layer sample. By making the pitch angle of the rotation of the order of the wavelength of the emitted photon, we can form a photonic crystal that will modify the radiation pattern of the molecule. The photon will be preferentially emitted along the rotation axis. These 1-D photonic band-gap structures in cholesteric liquid crystals possess three main advantages over conventional 1-D photonic crystals:

(1) Because the refractive index n varies gradually rather than abruptly in cholesterics, there are no losses into the waveguide modes, which in the case of conventional 1-D photonic crystals, arise from total internal reflection at the boundary between two consecutive layers with a different n. These waveguide losses can reach ~20%.

(2) High polarization purity for circular polarization of definite handedness can be reached for single emitters with both polarized and unpolarized emission;

(3) Liquid crystal hosts can provide tunability of a single-photon source by external fields.

In addition to emitter alignment and self-assembled structures with photonic band-gap properties, such a host with special treatment (oxygen depletion) can protect the emitters from bleaching.

Summary of the most important results for three years (see attached file, pages 1-3):

- We have achieved significant results under the current award. We have 56 journal publications and periodically published conference proceedings, 5 one-time publications in conference proceedings, were awarded one patent, delivered 17 other conference lectures and presentations with 9 invited presentations among them.

- Single-photon generation and characterization unit was successfully built and has currently the following modules:
  (1) Single photon source (SPS) on demand module (home built confocal fluorescence microscope with imaging software with pulsed laser excitation); (2) Single photon detection module for visible spectral range with Perkin Elmer Si single-photon counting avalanche photodetectors and cooled EM-CCD camera of Andor Technologies; (3) Single photon detection module for optical communication wavelengths. Either superconducting NbN detectors or Princeton Lightwave single photon counting detector can be fiber coupled with one of the output ports of module 1; (4) Photon statistic and fluorescence lifetime measurement module with TimeHarp200 PC card with 40 ps resolution for time correlated single-photon counting.

- 1-D photonic bandgap cholesteric liquid crystal hosts doped with single colloidal quantum dots (PbSe, CdSe, CdTe) or single dye molecules were prepared both for visible and optical communication wavelength fluorescence. Fluorescence of these emitters was investigated both in visible spectral range and at 1.5 um.

- Fluorescence antibunching of colloidal semiconductor quantum dots was achieved for the first time in 1-D photonic bandgap cholesteric liquid crystal hosts;

- Deterministically polarized fluorescence from single colloidal quantum dots (both circular and linear) was achieved for the first time at room temperature;

- 21 graduate and 11 undergraduate students were trained on the SPS unit during three-year project. In addition, more than 50 other undergraduate and 5 high school students participated in lecture-demonstrations of a SPS unit by Dr. Lukishova.

- Several groups of five University of Rochester Departments (The Institute of Optics, Department of Chemical Engineering, Department of Chemistry, Department of Electrical and Computer Engineering, Laboratory for Laser Energetics) used single-photon source unit or its modules in their research.

- Final report to BBN-technology as a collaborating company was delivered by Dr. Lukishova’s presentation. Continuation of this collaboration was discussed.

Detailed account of accomplishments during each year of this NSF award is listed below for each year separately.
FIRST YEAR PERIOD (Sept.2004-Sept.2005, see attached file pages 3-12):

During this first year period of funding, our main research and education activities have been focused on following problems:

* Constructing and building of optical, mechanical and electronics parts of a new instrument (single-photon-on-demand generation and characterization unit) for the visible spectral band, with location in the Institute of Optics, University of Rochester (Dr. Lukishova, Prof. Stroud, Prof. Novotny);

* Working on room-temperature dye-doped liquid-crystal samples' development for efficiency increase of a single photon source with two types of hosts (Dr. Lukishova):
  - glassy nematic liquid crystals,
  - glassy 1-D photonic bandgap cholesteric liquid crystals;

* Studying of single-molecule fluorescence in glassy nematic and 1-D photonic band-gap cholesteric liquid crystals with low fluorescence background (Dr. Lukishova);

* Development of superconducting NbN single-photon receivers for telecommunication wavelengths (Prof. Sobolewski);

* Sharing the new equipment with other research groups, for instance, (i) single-photon detector module has been used in research of Prof. Boyd's group on quantum imaging for correlations observation in conical emission from atomic sodium vapor; (ii) single-photon-statistics-measurement module was used separately at the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski's research on NbN receivers and in Dr. Schmid's nanometrology group;

* Students' training (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one undergraduate student and one graduate student built the new instrument; (ii) one undergraduate student worked with single-photon detection module for lecture demonstration of single-photon interference; (iii) one undergraduate student worked on sample preparation and single-molecule fluorescence imaging; (iii) two graduate and one master students worked on single-photon detector/receiver development for telecommunication wavelengths;

* Preparing a lecture demonstration of single-photon interference for undergraduate students, using the new equipment (Prof. Knox's course, Dr. Lukishova);

* Preparing the University of Rochester internal proposal to include both the new instrument and its separate modules as quantum optics/quantum information teaching laboratory for advanced seniors from three University of Rochester departments (Dr. Lukishova);

* Preparing and submission of journal publications/periodically published conference proceedings, one-time publications (see Activities File and separate Publications section of this Report);

* Five other conference presentations were made (four of them are invited lectures):


During this second-year funding period, our main research and education activities have been focused on following issues:

- Developing and optimizing single-photon-on-demand generation and characterization unit built during the first year for the visible spectral range and its preparation for using at telecommunication wavelengths (Dr. Lukishova, Prof. Stroud);

- Development of superconducting NbN single-photon receivers for telecommunication wavelengths (Prof. Sobolewski);

- Working on room-temperature, dye-doped liquid-crystal samples' development for efficiency and polarization purity enhancement of a single photon source. This year efforts were concentrated on the monomeric (fluid-like) nematic and cholesteric liquid crystal hosts (Dr. Lukishova);

- Studying of single-dye-molecule fluorescence in monomeric, 1-D photonic band-gap, cholesteric liquid crystals with low fluorescence background (Dr. Lukishova);

- Using CdSe colloidal semiconductor quantum dots as fluorescence emitters in liquid crystal hosts (Dr. Lukishova, Prof. Krauss);

- Sharing the new equipment with other research groups, for instance, (i) the single-photon detector module has been used in research of Prof. Boyd's group (the Institute of Optics) on spontaneous parametric down conversion and investigation of lasing in monomeric cholesteric liquid crystal doped with oligofluorene; (ii) the single-photon-statistics-measurement module was used separately in the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski research on NbN receivers and in Dr. Schmid's nanometrology group; (iii) single colloidal semiconductor quantum dots of Prof. Krauss (Department of Chemistry) were investigated on our setup both on bare glass substrates and inside liquid crystal hosts; (iv) we had negotiations regarding measurement of transient fluorescence with ~ 40 ps resolution of dyes attached to the DNA molecules on our unit with the Department of Chemistry (Prof. Rothberg); (v) we had negotiations with the Queens College of CUNY on using our setup for antibunching measurement in colloidal quantum dot fluorescence using 1-D photonic bandgap polymer structures fabricated in CUNY (Prof. Menon);

- Sixteen students' training was accomplished (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student is working on his Ph.D Thesis on this unit; (ii) two undergraduate students worked with different modules of the setup for two Summer months funded by an NSF REU Program; (iii) eight students from two University Departments (four graduate and four undergraduate) are learning the single-photon source unit as a part of the course 'Quantum Optics and Quantum Information Laboratory'; (iv) two graduate students work on single-photon detector/receiver development for telecommunication wavelengths; (v) three graduate students of Prof. Boyd worked with single-photon detection module.

- A lecture demonstration of single-photon interference for undergraduate students, using the new equipment (Prof. Knox's course, Dr. Lukishova);

- Outreach activity: Prof. Stroud prepared to include in his public lecture at Temple University, (October 2006) single-photon interference images made with new equipment;

- A new course 'Quantum Optics and Quantum Information Laboratory' was included in a Fall semester for both undergraduate and graduate students of three University Departments as a technical elective. Two teaching laboratory experiments were based on the single-photon source setup (Dr. Lukishova);

- An NSF Educational proposal was submitted to develop two more teaching experiments in quantum information as well as teaching strategy for this new field (Dr. Lukishova, Prof. Stroud, Prof. Knox). Monroe Community College students will be involved in training on photon-counting instrumentation.

* Preparing and submission of journal publications/periodically published conference proceedings, one-time publications (see Activities File pages 17-19 and separate Publications section of this Report);

* Eight other conference presentations were made (six of them are invited lectures):


7. Invited: 'Superconducting Single-Photon Optical Detectors Based on Superconducting Nanostructures,' R. Sobolewski, presented at the Texas Center for Superconductivity, University of Houston, Houston, TX, April, 2006.


THIRD YEAR PERIOD [(SEPT. 2006 - SEPT. 2007). See attached file, pages 22-32]:

During third-year funding period, our main research and education activities have been focused on following issues:

- Implementation of a single-photon-on-demand generation and characterization unit at telecommunication wavelength 1.5 µm using fluorescence of single colloidal PbSe semiconductor quantum dots in cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova, Prof. Stroud in collaboration with Prof. T. Krauss, Department of Chemistry, University of Rochester);

- Exhaustive testing of novel single-photon receivers, each based on two, fiber-coupled NbN superconducting single-photon detectors (SSPDs) (Prof. Sobolewski);

- Building of additional module to the single-photon generation and characterization unit for fiber coupling of 1.5 µm single photon counting detectors with this unit. For alignment of this system, a separate 1.5 µm diode laser was used (Dr. Lukishova);

- Obtaining of fluorescence antibunching of single colloidal semiconductor quantum dots in cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova in a collaboration with Prof. Boyd's group, the Institute of Optics, University of Rochester);

- Obtaining of high polarization purity of circularly polarized light from single colloidal semiconductor quantum dots in cholesteric liquid crystal hosts (Dr. Lukishova);

- Measurement of fluorescence spectrum of both hosts and colloidal semiconductor quantum dots (Dr. Lukishova);

- Measurements of fluorescence lifetimes of different colloidal semiconductor quantum dots (Dr. Lukishova);

- Working on room-temperature, quantum dot doped liquid-crystal samples' development for efficiency and polarization purity enhancement of a single photon source. This year efforts were concentrated both on the monomeric (fluid-like) cholesteric as well as glassy oligomeric cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova, in collaboration with Prof. S.H. Chen, Department of Chemical Engineering, University of Rochester);

- Investigation of semiconductor quantum dot fluorescence in other types of photonic bandgap materials (e.g., in nonchiral 1-D organic photonic bandgap structure with a defect layer). (Dr. Lukishova in collaboration with Prof. Menon, the Queens College of CUNY).

- Prof. Sobolewski, Dr. Lukishova and Prof. Krauss were awarded Technology Access Program (PTAP) Instrumentation Grant for Princeton Lightwave single-photon counting detector sensitive to 1.5 µm wavelength.

- Sharing the new equipment with other research groups, for instance, (i) the single-photon detector module has been used in research of Prof. Boyd's group (the Institute of Optics) on spontaneous parametric down conversion and quantum imaging; (ii) the single-photon-statistics-measurement module was used separately in the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski research on NbN receivers and in Dr. Schmid's nanometrology group; (iii) single colloidal semiconductor quantum dots of Prof.
Krauss (Department of Chemistry) were investigated on our setup both on bare glass substrates and inside various liquid crystal hosts; (iv) we had recent negotiations about the experiments of quantum dots fluorescence in immunoglobulin (IgG, IgM) using our confocal microscope setup (Department of Chemistry and Medical Center, University of Rochester);

- Prof. Stroud, Dr. Lukishova, Prof. Knox were awarded NSF educational grant (jointly with Monroe Community College) to develop teaching experiments in quantum information using photon counting instrumentation as well as teaching strategy for this new field.

- A course 'Quantum Optics and Quantum Information Laboratory' was continued in a 2007 Fall semester for both undergraduate and graduate students of three University Departments. Two teaching laboratory experiments were based on the single-photon source setup;

- Twelve students' training was accomplished during a third year of this project (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student from Optics is working on his Ph.D Thesis on this unit; (ii) six students from three University Departments (five graduate and one undergraduate) studied the single-photon source unit as a part of the course 'Quantum Optics and Quantum Information Laboratory' taught by Dr. Lukishova 2007 Fall semester; (iii) one graduate student works on single-photon detector/receiver development for telecommunication wavelengths; (iv) two graduate students of Prof. Krauss (Chemistry) worked on quantum dot synthesis for our samples and fluorescence detection at 1.55 &#956;m using single-photon counting detector; (v) one graduate student of Prof. Chen (Chemical Engineering) prepared photonic bandgap cholesteric liquid crystal samples doped with quantum dots. He also was trained on a single-photon unit by imaging single-quantum dot fluorescence in his samples; (vi) one graduate student of Prof. Menon (the Queens College, CUNY prepared 1-D photonic bandgap samples with defect layers doped with quantum dots.

- A lecture demonstration was delivered about single photon source setup for 26 undergraduate students, using the new equipment (Prof. Knox's course, Dr. Lukishova);

- Outreach activity: (i) Prof. Stroud included in his public lecture at Temple University, (October 2006) single-photon interference images recorded by EM-CCD camera; (ii) On March 22, 2007 approximately 75 high school and junior high school students from the Philadelphia area came to hear Prof. Stroud give a presentation on careers in optical science and engineering; (iii) On March 21, 2007 approximately 200 people attended a public evening lecture entitled 'Quantum Weirdness: Technology of the Future' that Prof. Stroud gave at Temple University in Philadelphia.

Findings:


FIRST YEAR PERIOD (Sept.2004-Sept.2005, see attached file pages 3-12):

Findings that have emerged from our group activities in a form of summarized conclusions are as follows:

- A new instrument was built: robust single-photon-on-demand-generation and characterization unit with pulsed laser excitation, providing both single-emitter fluorescence imaging and photon-statistic measurements;

- Deterministically polarized fluorescence from single emitters was observed for the first time;

- 1-D photonic band-gap structures in low-fluorescence-background cholesteric hosts doped with fluorescence emitters were prepared. We
succeeded in single-molecule fluorescence imaging of these structures, overcoming a challenge with host fluorescence;

* A novel, two-channel single-photon receiver for telecommunication wavelengths has been designed, implemented, and tested, based on two fiber-coupled NbN superconducting single-photon detectors;

* A lecture demonstration setup of single-photon interference for undergraduate students was made using the new equipment;

* Seven students' training was accomplished and proposal was written to use a new instrument in a quantum information teaching laboratory course;

* Twelve journal publications/periodically published conference proceedings, three one-time publications, five other conference presentations were made (four of them are invited lectures)
(See Activities File and Publication section of this Report).

SECOND YEAR PERIOD (Sept.2005-Sept.2006, see attached file pages 13-21):

Some of our results and findings with illustrations are described in attached Activities file (pages 13-21). Here are the highlights of our findings:

ò A new instrument (single-photon-on-demand-generation and characterization unit) provides both single-emitter fluorescence imaging and photon-statistic measurements with pulsed laser excitation (6 ps pulse duration and 76 MHz pulse repetition rate). For description of this instrument see pages 4-5. This robust unit with four output ports can also be used for transient fluorescence measurements with ~40-ps resolution;

ò Our experience with single dye molecule fluorescence in liquid crystal hosts shows much higher stability of the dye fluorescence in liquid crystal host (excitation periods of ~ 20 min or more without bleaching). At the same time single dye molecules on a bare glass surface are bleached very fast (~ 30 s or up to 3 min. with a polymethylmethacrylate coating) at comparable incident intensity;

ò 1-D photonic band-gap structures in low-fluorescence-background monomeric cholesteric hosts doped with single fluorescence emitters (dye molecules and quantum dots) were prepared with bandgap matching the emitter fluorescence band. We succeeded in single-dye-molecule fluorescence imaging of these structures, overcoming a challenge with host fluorescence. Our current single-photon source efficiency in such structures is ~10%. We are working on its further improvement;

ò We proved experimentally that single CdSe colloidal semiconductor quantum dots can fluoresce in both monomeric and oligomeric liquid crystal hosts. This is a major step toward a deterministically polarized and efficient single-photon source for telecommunication wavelength using PbSe quantum dots emitting at 1.55 um;

ò Our previous results on deterministically polarized fluorescence from single molecules of DiI dye in oligomeric nematic liquid crystal hosts were confirmed for monomeric liquid crystal hosts;

ò A novel, two-channel single-photon receiver for telecommunication wavelengths has been further tested, based on two fiber-coupled NbN superconducting single-photon detectors;

ò A course was prepared and is being taught on Quantum Optics and Quantum Information Laboratory using modules of the new instrument in two laboratory experiments;

ò Several research experiments were accomplished by other groups of Department using new instrumentation;

ò Twenty two journal publications/periodically published conference proceedings, four one-time publications, and eight other conference presentations and lectures were given.

THIRD YEAR PERIOD (Sept.2006-Sept.2007, see attached file pages 22-32):

ò A new instrument (single-photon-on-demand-generation and characterization unit) provides both single-emitter fluorescence imaging and photon-statistic measurements with pulsed laser excitation (6 ps pulse duration and 76 MHz pulse repetition rate) both in visible and near-IR spectral range including optical communication wavelength 1.5 um. Unit is robust and flexible to future single-photon detector development. It permits to use both free space and fiber coupled detectors.
1-D photonic band-gap structures doped with colloidal semiconductor quantum dots both for visible and 1.5 μm were prepared using cholesteric liquid crystal host (monomeric and glassy oligomeric).

We proved experimentally that single CdSe, CdTe, PbSe colloidal semiconductor quantum dots can fluoresce in both monomeric and oligomeric liquid crystal hosts;

A novel, two-channel single-photon receiver for telecommunication wavelengths has been further tested, based on two fiber-coupled NbN superconducting single-photon detectors;

A course was further developed and is being taught on Quantum Optics and Quantum Information Laboratory using modules of the new instrument in two laboratory experiments;

Several research experiments were accomplished by other groups using new instrumentation (see file, Part 5 of a third-year period);

Twenty two journal publications/periodically published conference proceedings, one one-time publications, and four other conference presentations and lectures were given (see file, Part 6).

**Training and Development:**

1. This project progresses with involvement of students of different levels (undergraduate, master and graduate students) from three University departments (Optics, Physics and Astronomy, Electrical and Computer Engineering) providing them training opportunities on cutting-edge equipment.

2. For instance, one graduate and one undergraduate student supervised by Prof. Stroud and Dr. Lukishova participated in building the new instrument. Both of them submitted Reports describing their activity.

3. Another undergraduate student's project supervised by Dr. Lukishova, was devoted to the arrangement of a single-photon interference setup for Prof. Knox's lecture demonstration. At the end of this work this student submitted a Report as well.

4. Two graduate and one master students supervised by Prof. Sobolewski were trained on the development of single-photon detector/receiver for telecommunication wavelengths.

5. Dr. Lukishova trained one more undergraduate student on sample preparation in a clean-room facility, on single-molecule fluorescence microscopy, and on photon statistics measurement.

6. As a result of thought of using this unique equipment for more efficient training, Dr. Lukishova prepared a proposal 'Interdisciplinary quantum optics and quantum information teaching laboratory - a new avenue for teaching entrepreneurship to engineering and physics students'. It will be submitted inside the University of Rochester as a teaching laboratory course for advanced seniors.

7. In 2006 Dr. Lukishova was awarded the University of Rochester Kauffman Initiative for her laboratory course on Quantum Optics and Quantum Information. Two laboratory experiments include single-photon source setup. From Fall 2006 Dr. Lukishova began to teach this course.

8. In 2006 Prof. Stroud, Dr. Lukishova, Prof. Knox submitted educational proposal to the NSF (jointly with Monroe Community College) on teaching experiments in the field of quantum optics and quantum information.

9. In 2006, sixteen students' training was accomplished (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student is working on his Ph.D Thesis on this unit; (ii) two undergraduate students worked with different modules of the setup for two Summer months funded by an NSF REU Program; (iii) eight students from two University Departments (four graduate and four undergraduate) are learning the single-photon source unit as a part of the course 'Quantum Optics and Quantum Information Laboratory'; (iv) two graduate students work on single-photon detector/receiver development for telecommunication wavelengths; (v) three graduate students of Prof. Boyd worked with single-photon detection module.
10. In 2006, more than twenty students of Prof. Knox course (three groups) participated in lecture-demonstration of a SPS setup by Dr. Lukishova.

11. In June 2007 Prof. Stroud, Dr. Lukishova, Prof. Knox (jointly with Monroe Community College) were awarded NSF educational grant on teaching experiments in the field of quantum optics and quantum information.

12. In the Fall of 2007 Dr. Lukishova continued to teach laboratory course on quantum optics and quantum information. Two teaching laboratories of this course are carried out on a current single-photon source unit. In addition to four graduate and four undergraduate students passed through this course in 2006, five graduate and one undergraduate (minority) students are currently enrolled in it.

13. Three groups of undergraduate students of Prof. Knox’s course (total 26 students) participated in November 2007 lecture-tour of a laboratory of Dr. Lukishova with a single-photon source setup.

14. Five other graduate students from different departments of University (Optics, Chemical Engineering, Chemistry, Electrical and Computer Engineering) worked for their PhD projects on a single-photon source unit, its modules or sample preparation.

15. Prospective graduate, undergraduate students and high-school students also participated in lecture-tour of Dr. Lukishova of year 2007.

16. After visit BBN Technologies by Dr. Lukishova, the negotiation was made about a participation of her students in Summer work of this company on quantum communication network system.

17. Graduate student from Queens College, CUNY who prepared some samples for a SPS unit was also involved in the project.

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SUMMARY FOR THREE YEARS:
21 graduate and 11 undergraduate students were trained on the SPS unit during three-year project. In addition, more than 50 other undergraduate and 5 high school students participated in lecture-demonstration of a SPS unit by Dr. Lukishova.

Outreach Activities:
1. On October 13, 14, 2005 Professor Carlos Stroud will visit Marshall University, Huntington, WV as a Distinguished Traveling Lecturer in Laser Science for the Division of Laser Science of the American Physical Society. As a part of this visit he will give a public lecture entitled ‘Quantum Weirdness: Technology of the Future?’ High school students and the general public will be invited to attend.

2. Other events planned include meeting with the Mayor of Huntington and the Chamber of Commerce to talk about physics and laser science as entrepreneurial assets to a college town.

In addition, he will give a physics colloquium and meet with various student and faculty groups.

3. Prof. Stroud actively participates in the outreach activity. He delivered a lecture to approximately 200 members of the general public at Marshall University (October 13, 2005) on the subject of ‘Quantum Weirdness.’

4. He also delivered a lecture to high school and middle school students from Huntington, West Virginia in October 14, 2005, on the subject of ‘Quantum Optical Engineers the Rocket Boys of the Future.’

5. This year Stroud scheduled to give similar outreach lectures at Temple University in October 2006. He will use single-photon interference images (see page 8, Fig. 16) recorded by EM-CCD camera.

6. March 22, 2007 - Approximately 75 high school and junior high school students from the Philadelphia area came to hear Prof. Stroud give a presentation on careers in optical science and engineering.

Journal Publications


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**Books or Other One-time Publications**


Collection: Technical Digest of the 11th International Topical Meeting on Optics of Liquid Crystals, October 2-7, 2005, Sand Key, Florida

Bibliography: CREOL, University of Central Florida
Collection: the Institute of Materials Physics, University of Vienna, Vienna, Austria, May 2006.
Bibliography: N/A

Collection: the Texas Center for Superconductivity, University of Houston, Houston, TX, April, 2006.
Bibliography: N/A

Bibliography: N/A

Editor(s): Optical Society of America
Bibliography: N/A

Web/Internet Site

URL(s):
http://speckle.inaoep.mx/QOII/ppts/Lukishova.pdf

Description:
This site presents a PowerPoint talk of the results of single-photon source for quantum information

Dr. Lukishova and Dr. Yakhnin prepared another site describing a single-photon source activity as well as teaching course "Quantum optics and quantum information laboratory". Currently web-addresses are:
http://optical-waveguides-modeling.net/rochester/single-photon-source.pdf and
http://optical-waveguides-modeling.net/rochester/QuantumOpticsQuantumInformationLabCourse.pdf

At the end of the year 2007 these websites will be moved to the Institute of Optics, University of Rochester site (Dr. Lukishova).

Other Specific Products

Product Type:
Instruments or equipment developed

Product Description:
A single-photon generation and characterization unit was developed and built. This instrument consists of three modules with specific functions (1) a single photon source module that represents a confocal fluorescence microscope built from a Nikon TE2000 Quantum inverted optical microscope with five output ports; (2) a single-photon detection module that comprises two cooled Si Perkin Elmer avalanche photodiodes (APDs), placed in each of two arms of a Hanbury Brown and Twiss setup, and a single-photon-sensitive electron multiplying, cooled CCD-camera from Andor Technologies; (3) a photon-statistics measurements module with time-correlated single-photon counting PC card TimeHarp 200 from PicoQuant. At a later stage, superconducting NbN detectors will be placed in a separate port of the microscope in addition to the Si APDs to extend the detection wavelength range of the instrument up to 2.5 microns (including the optical communication wavelengths).

Sharing Information:
This equipment was used beyond our group. The single photon generation and characterization unit consists of several modules which can be easily delivered to other groups. For instance, Prof. Boyd used our electron multiplying CCD camera for his experiments in quantum imaging. Computer with a TimeHarp card was used for correlation measurements at the Laboratory for Laser Energetics. We are planning to make a construction of optical part of a Hanbury Brown and Twiss setup more robust to use it in different setups with single-emitter excitation.

Product Type:
Proposal for quantum optics and quantum information teaching laboratory

Product Description:
Dr. Svetlana Lukishova prepared an inside university proposal to use the single-photon source instrument as a part of a quantum optics/quantum information teaching laboratory

Sharing Information:
Undergraduate students from three departments (Optics, Physics and Electrical Engineering and Computer Science) will work on research projects using this single-photon source instrument.

Product Type:
Teaching aids

Product Description:
Dr. Lukishova prepared the course "Quantum Optics and Quantum Information Laboratory" including manuals for this course.

Sharing Information:
From Fall semester of 2006 Dr. Lukishova teaches this course. All eight students received Laboratory Manuals with description of confocal fluorescence microscopy, single-photon source setup, photon counting instrumentation, antibunching measurements.

Dr. Lukishova continued to teach this course in a 2007 year Fall semester.

Contributions

Contributions within Discipline:
We demonstrated that our room-temperature, liquid-crystal-host single-photon source technique can exceed the alternative technology - cryogenic-temperature, single photon sources based on semiconductor heterostructures.

In addition to room-temperature operation, we provided evidence on deterministic polarization of single photons.

Different single fluorescence emitters (dye molecules, semiconductor nanocrystals, carbon nanotubes) can be easy dissolved/dispersed in liquid crystal hosts providing operation in spectral regions from UV to near-IR (including telecommunication wavelengths).

Photonic bandgaps in nanostructured liquid crystals will provide fluorescence line narrowing, increasing source efficiency, shortening of fluorescence lifetime and tunability of the source under temperature/electric field control.

1-D photonic band-gap structures in cholesteric liquid crystals possess an additional advantage over conventional 1-D micropost technologies which are used with heterostructures containing semiconductor quantum dots. Because the refractive index n varies gradually rather than abruptly in cholesterics, there are no losses into the waveguide modes, which in the case of micropost technology arise from total internal reflection at the border between two consecutive layers with different n. These waveguide losses can reach ~20%.

We observed for the first time at room temperature deterministically polarized fluorescence (both linear and circular) of single emitters

Contributions to Other Disciplines:
Our research is a multidisciplinary area. It includes quantum optics/quantum information science and technology, optical confocal single-molecule fluorescence microscopy, materials development.

Our main area is quantum optics/quantum information science and technology. We reported the contributions to this discipline in previous section of this Report. Our contributions to other disciplines are as follows:

(1) LIQUID CRYSTAL MATERIAL SCIENCE AND TECHNOLOGY:
-- Finding a new application of liquid crystals which may have impact on optical communication technology;

-- Developing a new technology of ultrahigh purification of liquid crystalline material for single-molecule fluorescence microscopy;

-- Developing a technology of planar-alignment of glassy liquid crystals on very thin substrates (~ 0.2 mm thickness);

(2) NANOTECHNOLOGY (PHOTONIC BANDGAP MATERIALS)

-- Developing photonic bandgap materials with tunable bandgaps by electric field/temperature control using nanostructured liquid crystals or photonic crystals infiltrated with liquid crystals;

(3) SINGLE-MOLECULE FLUORESCENCE MICROSCOPY

-- Developing the ways of reducing fluorescence emitter bleaching in the hosts by special host treatment.

(4) BIOMEDICINE

-- Investigating the new fluorescence markers (PbSe quantum dots) for 1.3 and 1.5 um spectral regions, transparent to human body.

Contributions to Human Resource Development:

1. This project provided an opportunity for seven students from three University of Rochester departments to be trained on cutting edge-equipment and developing skills in a multidisciplinary area.

2. In addition, we see the built instrument as a part of a quantum information teaching laboratory for undergraduate students of three departments of the University of Rochester (Optics, Physics, Electrical and Computer Engineering) who will participate in research projects on this setup. Students will write reports about practical application of their research and dissemination the results among public.

3. Sixteen students' training was accomplished during the second-year reporting period (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student is working on his Ph.D Thesis on this unit; (ii) two undergraduate students worked with different modules of the setup for two Summer months funded by an NSF REU Program; (iii) eight students from two University Departments (four graduate and four undergraduate) are learning the single-photon source unit as a part of the course 'Quantum Optics and Quantum Information Laboratory'; (iv) two graduate students work on single-photon detector/receiver development for telecommunication wavelengths.

4. More than fifty students of Prof. Knox course participated in lecture-demonstration of a SPS setup by Dr. Lukishova during the second and the third year of the project.

5. In the Fall of 2007 Dr. Lukishova continued to teach laboratory course on quantum optics and quantum information. In addition to four graduate and four undergraduate students passed through this course in 2006, five graduate and one undergraduate (minority) students are currently enrolled in it. From underrepresentative groups of students two women and one minority student participated in this course. This project involves also a collaboration with the local Community Colleges of Rochester/Corning area.

6. Four other graduate students from different departments of University (Optics, Chemical Engineering, Chemistry) worked on their projects on a single-photon source unit.

SUMMARY FOR THREE YEARS:

This project contributed to human resource development in science, engineering and technology by involving students in this project and training them on a SPS unit. Total 21 graduate and 11 undergraduate students were trained on the SPS unit during three-year project. In addition, more than 50 other undergraduate and 5 high school students participated in lecture-demonstrations of a SPS unit by Dr. Lukishova. Two women and one minority student from total 14 students passed through Dr. Lukishova laboratory course on quantum optics and quantum information with a SPS unit as teaching setup.

Our new NSF educational grant (jointly with Monroe Community College) with funding started from June 2007 will permit to improve our methods of teaching and attracting students to the modern science and engineering. Participating of Community College in this project with significant percent of underrepresented groups will contribute to human resource development as well.

Contributions to Resources for Research and Education:

1. This instrument will be used in summer school sessions of the Institute of Optics for visitors from industry.
2. Educational proposal was submitted to the NSF on Quantum Optics and Quantum Information teaching experiments. If awarded, students from three University of Rochester Departments and Monroe Community College will learn photon counting instrumentation and its applications in real world.

3. In June 2007 Prof. Stroud, Dr. Lukishova, Prof. Knox (jointly with Monroe Community College) were awarded NSF educational grant on teaching experiments in the field of quantum optics and quantum information. A SPS setup and its modules is the main experimental unit of this course.

4. In the Falls of 2006 and 2007 Dr. Lukishova taught a laboratory course on quantum optics and quantum information. Two teaching laboratories of this course are carried out on a current single-photon source unit. 14 students passed through her course during these two years.

5. Website was prepared on a SPS unit and quantum optics/quantum information laboratory course (see this report, website address)

Contributions Beyond Science and Engineering:
The single-photon source we are developing is a pivotal hardware element for quantum information technology which can revolutionize the lives of ordinary people.

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: if you try to measure the behavior of a quantum particle, you alter it in such a way that your measurement isn't completely accurate. This means if you send the encryption key using a sequence of single photons, no one can intercept them without your knowledge.

Practical quantum cryptography systems are already in the market but with very inefficient laser beams attenuated to the single-photon level. Only one of 10 laser shots in the currently sold systems produces a single photon. The unique properties of our instrument will be its extremely high repetition rate of single photons(up to ~100 MHz) with ultrafast detection of single photons with University-developed detectors.

In another implementation, a single-photon source becomes the key hardware element for extremely powerful quantum computers with linear optical elements and photodetectors.

Categories for which nothing is reported:
**Project goal:** This three-year-project’s goal is the development of a new instrument (*single photon generation and characterization unit*) satisfying the needs of several University of Rochester departments working in the field of quantum optics/quantum information, single photon detection/measurements, nanotechnology, fluorescence spectroscopy and microscopy. This instrument, a prototype of a key hardware for practical, absolutely secure quantum communications, is based on fluorescence of single emitters embedded in a host material. This project was carried out in contact with BBN Technologies, company which built first quantum communication network in Boston area.

The project also includes the development of samples with single emitters as well, for a *room-temperature* alternative to *cryogenic*-temperature single photon sources. For this purpose liquid crystal hosts with photonic bandgaps doped with single dye molecules or semiconductor colloidal quantum dots were developed.

The liquid crystal hosts which can exist both as monomers (fluid media) and oligomers/polyomers serve two purposes. Nematic liquid crystals align the dye molecules along a definite axis. Such aligned molecules would normally emit in a dipole pattern which is a big improvement over the more common situation in which the molecular axes, and thus the dipole patterns, are randomly oriented in space. The chiral nematic (cholesteric) liquid crystals further improve the situation by providing a photonic crystal environment into which the molecules will emit. This environment is provided by supplying a torque to the medium as it is being laid down. The liquid crystals are dichroic, and this torque causes the principal axis of the index of refraction to rotate periodically about an axis perpendicular to the thin layer sample. By making the pitch angle of the rotation of the order of the wavelength of the emitted photon, we can form a photonic crystal that will modify the radiation pattern of the molecule. The photon will be preferentially emitted along the rotation axis. These 1-D photonic band-gap structures in cholesteric liquid crystals possess three main advantages over conventional 1-D photonic crystals:

1. Because the refractive index \( n \) varies gradually rather than abruptly in cholesterics, there are no losses into the waveguide modes, which in the case of conventional 1-D photonic crystals, arise from total internal reflection at the boundary between two consecutive layers with a different \( n \). These waveguide losses can reach ~20%.

2. High polarization purity for circular polarization of definite handedness can be reached for single emitters with both polarized and unpolarized emission;

3. Liquid crystal hosts can provide tunability of a single-photon source by external fields.

In addition to emitter alignment and self-assembled structures with photonic band-gap properties, such a host *with special treatment* (oxygen depletion) can protect the emitters from bleaching.
Summary of the most important results for three years:

- We have achieved significant results under the current award. We have 56 journal publications and periodically published conference proceedings, 5 one-time publications in conference proceedings, were awarded one patent, delivered 17 other conference lectures and presentations with 9 invited presentations among them.
- Single-photon generation and characterization unit was successfully built (see Figure 1) and has currently the following modules: (1) Single photon source (SPS) on demand module (home built confocal fluorescence microscope with imaging software with pulsed laser excitation); (2) Single photon detection module for visible spectral range with Perkin Elmer Si single-photon counting avalanche photodetectors and cooled EM-CCD camera of Andor Technologies; (3) Single photon detection module for optical communication wavelengths. Either superconducting NbN detectors or Princeton Lightwave single photon counting detector can be fiber coupled with one of the output ports of module 1 (see Figure 1); (4) Photon statistic and fluorescence lifetime measurement module with TimeHarp200 PC card with 40 ps resolution for time correlated single-photon counting.

Figure 1. Photograph of a single photon generation and characterization unit with 1.5 μm single-photon counting detector module (right) fiber coupled with one of the output ports of a home-built confocal microscope module.

- 1-D photonic bandgap cholesteric liquid crystal hosts doped with single colloidal quantum dots (PbSe, CdSe, CdTe) or single dye molecules were prepared both for visible and optical communication wavelength fluorescence. Fluorescence of these emitters was investigated both in visible spectral range and at 1.5 μm.
- Fluorescence antibunching of colloidal semiconductor quantum dots was achieved for the first time in 1-D photonic bandgap cholesteric liquid crystal hosts;
- Deterministically polarized fluorescence from single colloidal quantum dots (both circular and linear) was achieved for the first time at room temperature;
- 21 graduate and 11 undergraduate students were trained on the SPS unit during three-year project. In addition, more than 50 other undergraduate and 5 high school students participated in lecture-demonstrations of a SPS unit by Dr. Lukishova.
- Several groups of five University of Rochester Departments (The Institute of Optics, Department of Chemical Engineering, Department of Chemistry, Department of Electrical
and Computer Engineering, Laboratory for Laser Energetics) used single-photon source unit or its modules in their research.

- Final report to BBN-technology as a collaborating company was delivered by Dr. Lukishova’s presentation. Continuation of this collaboration was discussed.

Detailed account of accomplishments during each year of this NSF award is listed below for each year separately.

**Project Activities and Findings (Sept. 04 –Sept. 05)**

**Award No:** ECS-0420888

**MRI: Development of single photon generation and characterization unit**

Carlos R. Stroud, Svetlana G. Lukishova, Lukas Novotny, Roman Sobolewski, Wayne H. Knox

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

During this first year period of funding, our main research and education activities have been focused on following problems:

- Constructing and building of optical, mechanical and electronics parts of a new instrument (*single-photon-on-demand generation and characterization unit*) for the visible spectral band, with location in the Institute of Optics, University of Rochester (Dr. Lukishova, Prof. Stroud, Prof. Novotny);

- Working on room-temperature dye-doped liquid-crystal samples’ development for efficiency increase of a single photon source with two types of hosts (Dr. Lukishova):
  - glassy *nematic* liquid crystals,
  - glassy 1-D photonic bandgap *cholesteric* liquid crystals;

- Studying of single-molecule fluorescence in glassy nematic and 1-D photonic band-gap cholesteric liquid crystals with low fluorescence background (Dr. Lukishova);

- Development of superconducting NbN single-photon receivers for telecommunication wavelengths (Prof. Sobolewski);

- Sharing the new equipment with other research groups, for instance, (i) single-photon detector module has been used in research of Prof. Boyd’s group on quantum imaging for correlations observation in conical emission from atomic sodium vapor; (ii) single-photon-statistics-measurement module was used separately in the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski research on NbN receivers and in Dr. Schmid’s nanometrology group;

- Students’ training (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one undergraduate student and one graduate student built the new instrument; (ii) one undergraduate student worked with single-photon detection module for lecture demonstration of single-photon interference; (iii) one undergraduate student worked on sample preparation and single-molecule fluorescence imaging; (iii) two graduate and one master students worked on single-photon detector/receiver development for telecommunication wavelengths;

- Preparing a lecture demonstration of single-photon interference for undergraduate students, using the new equipment (Prof. Knox’s course, Dr. Lukishova);

- Preparing the University of Rochester internal proposal to include both the new instrument and its separate modules as quantum optics/quantum information teaching laboratory for advanced seniors of three University of Rochester departments (Dr. Lukishova).
More details of our activities with the main results and findings are described below, in Parts 1-6 of this section of the Report. Here are the highlights of these findings:

- A new instrument was built (Part 1): robust single-photon-on-demand-generation and characterization unit with pulsed laser excitation, providing both single-emitter fluorescence imaging and photon-statistic measurements;
- Deterministically polarized fluorescence from single emitters was observed for the first time (Part 2.1);
- 1-D photonic band-gap structures in low-fluorescence-background cholesteric hosts doped with fluorescence emitters were prepared. We succeeded in single-molecule fluorescence imaging of these structures, overcoming a challenge with host fluorescence (Part 2.2);
- A novel, two-channel single-photon receiver for telecommunication wavelengths has been designed, implemented, and tested, based on two fiber-coupled NbN superconducting single-photon detectors (Part 3);
- A lecture demonstration setup of single-photon interference for undergraduate students was made using the new equipment (Part 4);
- Seven students’ training was accomplished and proposal was written to use a new instrument in a quantum information teaching laboratory course (Part 5);
- Twelve journal publications/periodically published conference proceedings, three one-time publications, four other conference presentations were made (Part 6).

Below is a more detailed listing of the above mentioned findings.

1. **Single-photon-on-demand-generation and -characterization unit**

The basic elements of the new instrument (Prof. Stroud and Dr. Lukishova) are shown in Figures 1 and 2. It consists of three modules with specific functions (1) a single photon source module that represents a confocal fluorescence microscope built from a Nikon TE2000 Quantum inverted optical microscope with five output ports; (2) a single-photon detection module that comprises two cooled Si Perkin Elmer avalanche photodiodes (APDs), placed in each of two arms of a Hanbury Brown and Twiss setup, and a single-photon-sensitive electron multiplying, cooled CCD-camera from Andor Technologies; (3) a photon-statistics measurements module with time-correlated single-photon counting PC card TimeHarp 200 from PicoQuant. At a later stage, superconducting NbN detectors (Prof. Sobolewski) will be fiber-connected with a separate port of the microscope in addition to the Si APDs (Figure 2), to extend the detection wavelength range of the instrument up to 2.5 μm (including telecommunication wavelengths).
The light source for the confocal microscope is a mode-locked, diode-pumped, 8-10 ps laser with 76 MHz pulse repetition rate @ 532 nm wavelength (Time Bandwidth Products). A piezoelectric two-dimensional, close-loop scan table from Mad City Labs with raster-scanning capability is used in moving the sample transversely to the optical axis. The electronics consist of a National Instruments (NI) controller board for controlling the scan and NI counter DAQ board for counting the signals from the APDs. LabView based imaging software (Prof. Novotny, collaboration with Dr. A. Lieb, University of Basel) provides raster-scan images of single-molecule fluorescence from an area up to 50 μm x 50 μm. Figure 3 shows the user interface of the imaging software.

Figure 2. The basic elements of the instrument (including future superconducting NbN detectors).

Figure 3. User interface of a LabView based imaging software.

Figure 4. Superconducting NbN single photon receiver set up: top-left – fiber optical input; bottom left - electronics; right – cryogenic Dewar with superconducting NbN-detectors inside.
Prof. Sobolewski’s group has designed, implemented, and tested a novel, two-channel single-photon receiver, based on two fiber-coupled NbN superconducting single-photon detectors (SSPDs) for telecommunication wavelength (Figure 4), that in the future can be coupled with one of the free output ports of the built instrument (single-photon-generation and characterization unit).

2. Sample preparation and single-molecule fluorescence imaging of the samples

2.1. Deterministically polarized fluorescence from single dye molecules aligned in glassy nematic liquid crystal hosts

We demonstrated for the first time (to our knowledge) a deterministically polarized fluorescence from single emitters (Dr. Lukishova, Prof. Stroud in collaboration with Dr. Schmid, Laboratory for Laser Energetics and Prof. Boyd, the Institute of Optics, University of Rochester). The liquid-crystal-material part of this work was made in a collaboration with Prof. S.H. Chen, Department of Chemical Engineering, University of Rochester whose group synthesized the liquid crystal oligomer with low fluorescence background. The nematic liquid crystal state of this material (N) can be preserved at room temperature by slowly cooling it to the glassy state (G) with frozen nematic order. Figure 5 shows the molecular structure of Chen’s oligomer and the heating/cooling diagrams. We prepared ~100-nm-thickness films of this dye-doped glassy nematic liquid crystal aligned in deterministic direction by linear polarized UV-light (photoalignment). This new alignment technique (collaboration with K. Marshall, Laboratory for Laser Energetics, University of Rochester) excluding contamination of the material, in the case of liquid crystal oligomer which is solid at room temperature needs a strict annealing regime for a good-quality alignment to prevent destruction of the film during heating/cooling process. We succeeded in preparation of such alignment (Figure 6) across an area of at least 10 mm x 10 mm.

Figures 7 and 8 illustrate deterministically polarized fluorescence from single dye molecules in planar-aligned glassy nematic liquid crystal host under 532-nm, cw-excitation. Polarization
anisotropy is defined here as \( \rho = (I_{\text{par}} - I_{\text{perp}}) / (I_{\text{par}} + I_{\text{perp}}) \), where \( I_{\text{par}} \) and \( I_{\text{perp}} \) are fluorescence intensities for polarization components parallel and perpendicular to the alignment direction. These two polarization components in the plane of the sample have been separated with a polarizing beamsplitter cube. For DiIC\(_{18}(3)\) dye the polarization direction of the fluorescence of single molecules is predominantly in the direction perpendicular to the alignment of liquid crystal molecules.

The same sign of the polarization anisotropy was obtained for the sample with high (~1%) concentration of the DiIC\(_{18}(3)\) dye in planar aligned glassy nematic liquid crystal film with ~ 2 \( \mu \)m thickness. Spectrofluorimeter measurements of the fluorescence spectra from this sample for two polarization components are depicted in Figure 9 (\( \rho \approx -0.6 \)) showing significant higher intensity for perpendicular polarization in comparison with parallel polarization. This predominance of “perpendicular” polarization can be explained by DiIC\(_{18}(3)\)’s molecular structure (Figure 10). Likely, two alkyl chains oriented parallel to the rod-like liquid crystal molecules, but emitting/absorbing dipoles which are parallel to the bridge (perpendicular to alkyl chains) will be directed perpendicular to the alignment.

\[ \text{Figure 7. Confocal fluorescence microscopy images of DiIC}_{18}(3) \] single-molecule fluorescence in planar aligned glassy nematic liquid crystal host (10 \( \mu \)m x 10 \( \mu \)m scan): left – polarization perpendicular to the alignment direction; right – “parallel” polarization. Both images have the same background level.

\[ \text{Figure 8. The histogram of polarization anisotropy of 38 molecules of DiIC}_{18}(3) \] dye in planar aligned glassy nematic liquid crystal host.

\[ \text{Figure 9. Fluorescence spectra of DiIC}_{18}(3) \] dye in planar aligned glassy nematic liquid crystal host for different polarizations under the excitation with a nonpolarized, 532 nm light (1% concentration by weight).

\[ \text{Figure 10. Molecular structure of DiIC}_{18}(3): \] absorbing and emitting dipoles are parallel to the bridge (perpendicular to two alkyl chains).
2.2. Single-molecule fluorescence in 1-D photonic band-gap glassy cholesteric liquid crystals with low fluorescence background

This work (Dr. Lukishova, Prof. Stroud) was carried out in collaboration with Dr. Schmid (Laboratory for Laser Energetics, University of Rochester), Prof. Boyd (the Institute of Optics, University of Rochester), Prof. S.H. Chen (Department of Chemical Engineering, University of Rochester) and Cornerstone Research Group (Dayton, OH). Cornerstone Research Group synthesized two types of liquid crystal oligomers with low fluorescence background. The chiral compound (Figure 11, top) can be mixed in solution with the nematic compound (see Section 3 of this Report or Figure 11, bottom) in different proportions, and after several procedures (spin-coating on a photoaligned polymer, heating and slow annealing) 1-D photonic band-gap cholesteric structures can be frozen in a glassy state. Bandgap position depends on the relative concentration of the compounds. Transmission in the band center depends on the glassy-layer thickness. Figure 12 shows a selective reflection band matched with the fluorescence maximum of DiIC\textsubscript{18}(3) dye (~579 nm) which should be on a band-edge for maximum fluorescence efficiency.

![Molecular structure of chiral (top) and nematic (bottom) liquid crystal oligomers.](image1)

![Selective reflection band of 1-D photonic band-gap cholesteric liquid crystal structure with low fluorescence background (spin coating (~ 100 nm film thickness)).](image2)

We succeeded in single-molecule fluorescence imaging of these structures, overcoming a challenge with host fluorescence. Single-molecule fluorescence images in low-background glassy liquid crystals from Cornerstone Research Group are presented in Figure 13 for nematic material (left), and cholesteric 1-D photonic band-gap structure (right).

![Confocal fluorescence microscopy images of single-molecule fluorescence in glassy nematic (left) and cholesteric 1-D photonic band-gap structure (right).](image3)
3. Development of superconducting NbN single-photon receivers for telecommunication wavelength

During the current year, we continued our progress on the design and development of a quantum communications channel for the practical Quantum Key Distribution (QKD) system (Prof. Sobolewski). In particular, we have designed, implemented, and tested a novel, two-channel single-photon receiver, based on two fiber-coupled NbN superconducting single-photon detectors (SSPDs). The receiver is intended for fiber-based QKD systems, operational at telecommunication wavelengths. Coupling between the SSPD detector and a single-mode optical fiber has been achieved using a specially designed, micromechanical photoresist ring, positioned directly over the NbN detector active area. The positioning accuracy of the ring is below 1 micrometer. The receiver with SSPDs is placed (immersed) in a standard liquid-helium transport Dewar and can operate at 4.2 K without interruption for over two months. At the same time, the optical fiber inputs and electrical outputs are kept outside the Dewar, so from the operator's point of view the receiver can be regarded as a room-temperature system.

In addition to Figure 4, Figure 14 shows integrated telecommunication wavelength single photon receiver for quantum communications. Two SSPDs are immersed in a liquid-helium transport dewar (Figure 4). Fiber delivers optical input directly to SSPD.

Figure 14. Integrated telecommunication wavelength single photon receiver.

Prof. Sobolewski has also worked on the physics of the single photon detection mechanism in nanostructured superconducting stripes, studying the dynamics of the hotspot formation, the photoresponse speed, and the origin of dark counts in SSPDs.
4. Setup for lecture demonstration of a single-photon interference for undergraduate students

Young’s double slit single-photon interference set up was prepared for lecture demonstration of Prof. Knox’s course OPT 101: *Optics in the Information Age*, using the single-photon detection module of the new instrument. Figure 15 shows a demonstration set up with Andor Technology electron multiplying, cooled CCD camera (right). Recording interference patterns are presented in Figure 16 for time interval 1 s (top) and 30 s (bottom). One undergraduate student worked on this research project.

![Figure 15. Single-photon interference setup for lecture demonstration.](image1)

![Figure 16. Young-double-slit single-photon interference: top – 1s accumulation time; bottom –30 s.](image2)

5. Research training, education and public outreach

This project progresses with involvement of students of different levels (undergraduate, master and graduate students) from three University departments (Optics, Physics and Astronomy, Electrical and Computer Engineering) providing them training opportunities on cutting-edge equipment. For instance, one graduate and one undergraduate student supervised by Prof. Stroud and Dr. Lukishova participated in building the new instrument. Both of them submitted Reports describing their activity. Another undergraduate student’s project supervised by Dr. Lukishova, was devoted to the arrangement of a single-photon interference setup for Prof. Knox’s lecture demonstration described in Part 4. At the end of this work this student submitted a Report as well. Two graduate and one master students supervised by Prof. Sobolewski were trained on the development of single-photon detector/receiver for telecommunication wavelengths. Dr. Lukishova trained one more undergraduate student on sample preparation in a clean-room facility, on single-molecule fluorescence microscopy, and on photon statistics measurement.

As a results of thoughts of using this unique equipment for more efficient training, Dr. Lukishova prepared a proposal “Interdisciplinary quantum optics and quantum information teaching laboratory – a new avenue for teaching entrepreneurship to engineering and physics students”. It will be submitted inside the University of Rochester as a teaching laboratory course for advanced seniors. In this course, in addition to student training in quantum information technology equipment, they will be expected to think about transformation of the idea into the market value. A new, not fully established yet market for quantum information technology will
be discussed and compared with the history of already developed, laser market that was grown initially from the “unpractical” idea.

6. Publications and conference presentations reflected the work under this award

6.1. Journal publications and periodically published conference proceedings


6.2. One-time publications in conference proceedings


6.3. Other conference lectures and presentations


During this second-year funding period, our main research and education activities have been focused on following issues:

- Developing and optimizing single-photon-on-demand generation and characterization unit built during the first year for the visible spectral range and its preparation for using at telecommunication wavelengths (Dr. Lukishova, Prof. Stroud);
- Development of superconducting NbN single-photon receivers for telecommunication wavelengths (Prof. Sobolewski);
- Working on room-temperature, dye-doped liquid-crystal samples’ development for efficiency and polarization purity enhancement of a single photon source. This year efforts were concentrated on the monomeric (fluid-like) nematic and cholesteric liquid crystal hosts (Dr. Lukishova);
- Studying of single-dye-molecule fluorescence in monomeric, 1-D photonic band-gap, cholesteric liquid crystals with low fluorescence background (Dr. Lukishova);
- Using CdSe colloidal semiconductor quantum dots as fluorescence emitters in liquid crystal hosts (Dr. Lukishova, Prof. Krauss);
- Sharing the new equipment with other research groups, for instance, (i) the single-photon detector module has been used in research of Prof. Boyd’s group (the Institute of Optics) on spontaneous parametric down conversion and investigation of lasing in monomeric cholesteric liquid crystal doped with oligofluorene; (ii) the single-photon-statistics-measurement module was used separately in the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski research on NbN receivers and in Dr. Schmid’s nanometrology group; (iii) single colloidal semiconductor quantum dots of Prof. Krauss (Department of Chemistry) were investigated on our setup both on bare glass substrates and inside liquid crystal hosts; (iv) we had negotiations regarding measurement of transient fluorescence with ~ 40 ps resolution of dyes attached to the DNA molecules on our unit with the Department of Chemistry (Prof. Rothberg); (v) we had negotiations with the Queens College of CUNY on using our setup for antibunching measurement in colloidal quantum dot fluorescence using 1-D photonic bandgap polymer structures fabricated in CUNY (Prof. Menon);
- Sixteen students’ training was accomplished (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student is working on his Ph.D Thesis on this unit; (ii) two undergraduate students worked with different modules of the setup for two Summer months funded by an NSF REU Program; (iii) eight students from two University Departments (four graduate and four undergraduate) are learning the single-photon source unit as a part of the course “Quantum Optics and Quantum Information Laboratory”; (iv) two graduate students work on single-photon detector/receiver development for telecommunication wavelengths; (v) three graduate students of Prof. Boyd worked with single-photon detection module.
- A lecture demonstration of single-photon interference for undergraduate students, using the new equipment (Prof. Knox’s course, Dr. Lukishova);
Outreach activity: Prof. Stroud prepared to include in his public lecture at Temple University, (October 2006) single-photon interference images made with new equipment;

A new course “Quantum Optics and Quantum Information Laboratory” was included in a Fall semester for both undergraduate and graduate students of three University Departments as a technical elective. Two teaching laboratory experiments were based on the single-photon source setup;

An NSF Educational proposal was submitted to develop two more teaching experiments in quantum information as well as teaching strategy for this new field (Dr. Lukishova, Prof. Stroud, Prof. Knox). Monroe Community College students will be involved in training on photon-counting instrumentation.

Some of our results and findings from these activities are described below, in Parts 1-6 of this section of the Report. Here are the highlights of our findings:

- A new instrument (single-photon-on-demand-generation and –characterization unit) provides both single-emitter fluorescence imaging and photon-statistic measurements with pulsed laser excitation (6 ps pulse duration and 76 MHz pulse repetition rate). For description of this instrument see pages 2-3. This robust unit with four output ports can also be used for transient fluorescence measurements with ~40-ps resolution;

- Our experience with single dye molecule fluorescence in liquid crystal hosts shows much higher stability of the dye fluorescence in liquid crystal host (excitation periods of ~ 20 min or more without bleaching). At the same time single dye molecules on a bare glass surface are bleached very fast (~ 30 s or up to 3 min. with a polymethylmethacrylate coating) at comparable incident intensity;

- 1-D photonic band-gap structures in low-fluorescence-background monomeric cholesteric hosts doped with single fluorescence emitters (dye molecules and quantum dots) were prepared with bandgap matching the emitter fluorescence band. We succeeded in single-dye-molecule fluorescence imaging of these structures, overcoming a challenge with host fluorescence. Our current single-photon source efficiency in such structures is ~10%. We are working on its further improvement (Part 1);

- We proved experimentally that single CdSe colloidal semiconductor quantum dots can fluoresce in both monomeric and oligomeric liquid crystal hosts (Part 2). This is a major step toward a deterministically polarized and efficient single-photon source for telecommunication wavelength using PbSe quantum dots emitting at 1.55 μm;

- Our previous results on deterministically polarized fluorescence from single molecules of DiI dye in oligomeric nematic liquid crystal hosts were confirmed for monomeric liquid crystal hosts (Part 3);

- A novel, two-channel single-photon receiver for telecommunication wavelengths has been further tested, based on two fiber-coupled NbN superconducting single-photon detectors;

- A course was prepared and is being taught on Quantum Optics and Quantum Information Laboratory using modules of the new instrument in two laboratory experiments (Part 4);

- Several research experiments were accomplished by other groups of Department using new instrumentation (Part 5);

- Twenty two journal publications/periodically published conference proceedings, four one-time publications, and eight other conference presentations and lectures were given (Part 6).
Below is a more detailed listing of some of the above mentioned findings.

1. **Single-emitter fluorescence in 1-D photonic band-gap monomeric cholesteric liquid crystals with low fluorescence background**

We used two types of fluorescent emitters: DiI dye and CdSe colloidal semiconductor quantum dots with fluorescence maximum near 580 nm (Figure 1). 1-D chiral nematic (cholesteric) photonic bandgap structures were prepared from monomeric liquid crystal nematic mixture E7 and chiral additive CB15 doped with these emitters at the concentration of ~10 nM. Figure 2 shows a schematic of selective reflection of such structure. Selective reflection curves of prepared samples for the right-handed-circular polarized light for the case of bandgap matching with emitter fluorescence band are depicted in Figure 3. Light-blue line shows no bandgap for the left-handed circular polarization component.

![Figure 1](image1.png)

**Figure 1.** Spectrofluorimeter measurements of fluorescence spectra of CdSe quantum dot (left) and DiI dye (right) under 532-nm excitation.

![Figure 2](image2.png)

**Figure 2.** Schematic of chiral 1-D photonic bandgap cholesteric liquid crystal structure.

![Figure 3](image3.png)

**Figure 3.** Selective reflection curves of prepared cholesteric photonic bandgap structures for right-handed circular polarized light. No selective reflection was observed for left-handed circular polarized light (light blue line).
Figure 4 shows single-dye molecule fluorescence in monomeric liquid crystal hosts using raster scan in confocal fluorescence microscopy (left and center) and electron-multiplying (EM) low-light CCD-camera (right image). Left and center images are obtained for 1-D photonic bandgap cholesteric liquid crystal structure, right image – for a planar-aligned nematic liquid crystal layer.

![Image of Figure 4](image1)

Figure 4. Single-molecule fluorescence imaging of DiI dye in liquid crystal hosts: left and center images (1-D photonic bandgap cholesteric structure) – raster scan of 10 μm x 10 μm (left) and 40 μm x 40 μm (center) and EMCCD image of planar-aligned nematic layer (right).

Figure 5 shows images of CdSe single quantum dot fluorescence in 1-D-photonic bandgap cholesteric liquid crystal using raster scan (left) and EM-CCD-camera imaging (right).

![Image of Figure 5](image2)

Figure 5. Single-quantum dot fluorescence imaging in 1-D cholesteric liquid crystal host by 40 μm x 40 μm raster scan (left) and EM-CCD-camera (right).

We reached single-photon source efficiency ~10% using 1-D cholesteric photonic bandgap structures.

2. **Deterministically polarized fluorescence from single dye molecules aligned in monomeric nematic liquid-crystal hosts**

Even simple alignment technique, e.g., shifting the substrates in one direction provided linear polarization preference on one polarization. Figure 6 shows the dependence of count rate for single-DiI-dye molecules versus incident linear polarization (a half-waveplate rotation) showing its dependence on the incident polarization angle.

![Figure 6](image)

**Figure 6.** Modulation of fluorescence of single DiI molecule as a function of incident polarization.

### 3. Research training, education and public outreach

As it was mentioned earlier, training of sixteen students was accomplished during the reporting period. (see page 11). Most of them learned both the whole single-photon source setup, imaging of single-emitter fluorescence and photon statistics (antibunching correlations) measurements. Some students worked only on separate modules of the instrument. For example, Figure 7, left shows the EM-CCD camera image obtained by REU Summer student supported by the NSF (advisor – Dr. Lukishova) of spontaneous parametric down conversion cone of photons from type I BBO crystal. EM-CCD camera was used in this experiment on a generation of polarization entangled photons and Bell’s inequality violation. The same student worked on a single-photon interference in Mach-Zehnder interferometer using this camera. Figure 7, center and right shows interference fringes at the output of interferometer with different accumulation time.

![Figure 7](image)

**Figure 7.** Example of student training using MRI-grant-equipment: left—spontaneous parametric down conversion cone of photons at the output of type I BBO crystal; center and right – interference fringes at the output of Mach-Zehnder interferometer (single-photon interference experiment).
A PI of this project Prof. Stroud actively participates in the outreach activity. He delivered a lecture to approximately 200 members of the general public at Marshall University (October 13, 2005) on the subject of “Quantum Weirdness.” He also delivered a lecture to high school and middle school students from Huntington, West Virginia in October 14, 2005, on the subject of “Quantum Optical Engineers the Rocket Boys of the Future.” This year Stroud scheduled to give similar outreach lectures at Temple University in October 2006. He will use single-photon interference images (see page 8, Fig. 16) recorded by EM-CCD camera.

4. Other group experiments on unit modules

Part of photon detection module, EM-CCD camera is practically in use almost every day both in single-photon source setup, student training and in research of other groups of the Institute of Optics. For example, in our collaborative research with Prof. Boyd and S.-H. Chen (Department of Chemistry) on dye-doped cholesteric liquid crystal laser this camera was used to record a spatial distribution at the output of cholesteric laser with a high dynamic range. Figure 8 shows a cholesteric laser beam cross-section in the case of a single-mode lasing (left) and for multimode case (right). Using almost the same 1-D photonic bandgap monomeric cholesteric structures as we used in a single-photon source research, but with much higher dye concentration, this collaboration will facilitate a selection of the optimum position of dye fluorescence maximum at the band-edge of such structure for the efficient single-photon source.

Figure 9 shows the results of using EM-CCD-camera in research of Boyd group 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 8. Beam cross-sections at the output of cholesteric liquid crystal laser for single-mode lasing (left) and multimode case (right). (Collaboration with Boyd and Chen groups).

Figure 9. Spontaneous parametric down conversion cones at the output of type II BBO crystal at different crystal angles with respect to the incident beam polarization. (Results of Boyd group).
6. Publications and conference presentations reflected the work under this award

6.1. Journal publications and periodically published conference proceedings


6.2. One-time publications in conference proceedings


6.3. Other conference lectures and presentations


7. *Invited:* "Superconducting Single-Photon Optical Detectors Based on Superconducting Nanostructures," R. Sobolewski, presented at the Texas Center for Superconductivity, University of Houston, Houston, TX, April, 2006.

During third-year funding period, our main research and education activities have been focused on following issues:

- Implementation of a single-photon-on-demand generation and characterization unit at telecommunication wavelength 1.5 μm using fluorescence of single colloidal PbSe semiconductor quantum dots in cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova, Prof. Stroud in collaboration with Prof. T. Krauss, Department of Chemistry, University of Rochester);

- Exhaustive testing of novel single-photon receivers, each based on two, fiber-coupled NbN superconducting single-photon detectors (SSPDs) (Prof. Sobolewski);

- Building of additional module to the single-photon generation and characterization unit for fiber coupling of 1.5 μm single photon counting detectors with this unit. For alignment of this system, a separate 1.5 μm diode laser was used (Dr. Lukishova);

- Obtaining of fluorescence antibunching of single colloidal semiconductor quantum dots in cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova in a collaboration with Prof. Boyd’s group, the Institute of Optics, University of Rochester);

- Obtaining of high polarization purity of circularly polarized light from single colloidal semiconductor quantum dots in cholesteric liquid crystal hosts (Dr. Lukishova);

- Measurement of fluorescence spectrum of both hosts and colloidal semiconductor quantum dots (Dr. Lukishova);

- Measurements of fluorescence lifetimes of different colloidal semiconductor quantum dots (Dr. Lukishova);

- Working on room-temperature, quantum dot doped liquid-crystal samples’ development for efficiency and polarization purity enhancement of a single photon source. This year efforts were concentrated both on the monomeric (fluid-like) cholesteric as well as glassy oligomeric cholesteric photonic bandgap liquid crystal hosts (Dr. Lukishova, in collaboration with Prof. S.H. Chen, Department of Chemical Engineering, University of Rochester);

- Investigation of semiconductor quantum dot fluorescence in other types of photonic bandgap materials (e.g., in nonchiral 1-D organic photonic bandgap structure with a defect layer). (Dr. Lukishova in collaboration with Prof. Menon, the Queens College of CUNY).

- Prof. Sobolewski, Dr. Lukishova and Prof. Krauss were awarded Technology Access Program (PTAP) Instrumentation Grant for Princeton Lightwave single-photon counting detector sensitive to 1.5 μm wavelength.

- Sharing the new equipment with other research groups, for instance, (i) the single-photon detector module has been used in research of Prof. Boyd’s group (the Institute of Optics) on spontaneous parametric down conversion and quantum imaging; (ii) the single-photon-statistics-measurement module was used separately in the Laboratory for Laser Energetics, University of Rochester, both in Prof. Sobolewski research on NbN receivers and in Dr. Schmid’s nanometrology group; (iii) single colloidal semiconductor quantum dots of Prof.
Krauss (Department of Chemistry) were investigated on our setup both on bare glass substrates and inside various liquid crystal hosts; (iv) we had recent negotiations about the experiments of quantum dots fluorescence in immunoglobulin (IgG, IgM) using our confocal microscope set up (Department of Chemistry and Medical Center, University of Rochester);

• Prof. Stroud, Dr. Lukishova, Prof. Knox were awarded NSF educational grant (jointly with Monroe Community College) to develop teaching experiments in quantum information using photon counting instrumentation as well as teaching strategy for this new field.

• A course “Quantum Optics and Quantum Information Laboratory” was continued in a 2007 Fall semester for both undergraduate and graduate students of three University Departments. Two teaching laboratory experiments were based on the single-photon source setup;

• Twelve students’ training was accomplished during a third year of this project (Prof. Stroud, Dr. Lukishova, Prof. Sobolewski): (i) one graduate student from Optics is working on his Ph.D Thesis on this unit; (ii) six students from three University Departments (five graduate and one undergraduate) studied the single-photon source unit as a part of the course “Quantum Optics and Quantum Information Laboratory” taught by Dr. Lukishova 2007 Fall semester; (iii) one graduate student works on single-photon detector/receiver development for telecommunication wavelengths; (iv) two graduate students of Prof. Krauss (Chemistry) worked on quantum dot synthesis for our samples and fluorescence detection at 1.55 μm using single-photon counting detector; (v) one graduate student of Prof. Chen (Chemical Engineering) prepared photonic bandgap cholesteric liquid crystal samples doped with quantum dots. He also was trained on a single-photon unit by imaging single-quantum dot fluorescence in his samples; (vi) one graduate student of Prof. Menon (the Queens College, CUNY prepared 1-D photonic bandgap samples with defect layers doped with quantum dots.

• A lecture demonstration was delivered about single photon source setup for 26 undergraduate students, using the new equipment (Prof. Knox’s course, Dr. Lukishova);

• Outreach activity: (i) Prof. Stroud included in his public lecture at Temple University, (October 2006) single-photon interference images recorded by EM-CCD camera; (ii) On March 22, 2007 approximately 75 high school and junior high school students from the Philadelphia area came to hear Prof. Stroud give a presentation on careers in optical science and engineering; (iii) On March 21, 2007 approximately 200 people attended a public evening lecture entitled 'Quantum Weirdness: Technology of the Future' that Prof. Stroud gave at Temple University in Philadelphia.

Some of our results and findings from the third year activities are described below, in Parts 1-6 of this section of the Report. Here are the highlights of our findings:

• A new instrument (single-photon-on-demand-generation and –characterization unit) provides both single-emitter fluorescence imaging and photon-statistic measurements with pulsed laser excitation (6 ps pulse duration and 76 MHz pulse repetition rate) both in visible and near-IR spectral range including optical communication wavelength 1.5 μm. Unit is robust and flexible to future single-photon detector development. It permits to use both free space and fiber coupled detectors.

• 1-D photonic band-gap structures doped with colloidal semiconductor quantum dots both for visible and 1.5 μm were prepared using cholesteric liquid crystal host (monomeric and glassy oligomeric).

• We proved experimentally that single CdSe, CdTe, PbSe colloidal semiconductor quantum dots can fluoresce in both monomeric and oligomeric liquid crystal hosts.
A novel, two-channel single-photon receiver for telecommunication wavelengths has been further tested, based on two fiber-coupled NbN superconducting single-photon detectors;

A course was further developed and is being taught on Quantum Optics and Quantum Information Laboratory using modules of the new instrument in two laboratory experiments;

Several research experiments were accomplished by other groups using new instrumentation (Part 5);

Twenty two journal publications/periodically published conference proceedings, one one-time publications, and four other conference presentations and lectures were given (Part 6).

Below is a more detailed listing of some of the above mentioned findings.

1. Single photon generation and characterization unit for visible and near-IR (including 1.5 μm) spectral regions

A new detection module fiber coupled with a confocal microscope output port was added to a single photon unit for detection of a single photons at 1.5 μm. Either superconducting NbN detector or Princeton Lightwave single photon receiver (Figure 1) can be used. 1.5 μm diode laser beam was used for alignment of a fiber-coupling system (Figure 1).

Figure 1. A new detection module fiber coupled with a confocal microscope output port. Princeton Lightwave single-photon receiver is seen at the upper right corner of the photograph.

This year was devoted to investigation of colloidal quantum fluorescence in 1-D photonic bandgap liquid crystal hosts both in monomeric (fluid-like) anf oligomeric (glassy) state. For fluorescence at optical communication wavelength PbSe colloidal quantum dots were synthesized by Prof. Krauss group (Department of Chemistry).

Figure 2, left shows single CdSe QD fluorescence images in a CLC host. Note that the dark horizontal stripes in the pattern are the result of single QD blinking, which is a characteristic property of single-QD fluorescence. See also Figure 3, left.
Figure 2. Left: A typical confocal fluorescence images of a single CdSe quantum dots in CLC host (15 μm x 15 μm scan). Right: Selective transmission of four different chiral photonic bandgap cholesteric liquid crystal hosts (blue lines) and the fluorescence spectrum of the CdSe quantum dots (red line).

The samples were prepared by mixing a highly diluted solution of CdSe QDs with a monomeric (fluid-like) CLC. CLCs with different pitch of chiral structure were prepared by selection of proper concentration of chiral additive CB15 in nematic E7. The QD-doped CLC was placed between two cover glass slips and planar aligned through uni-directional mechanical motion between the two slides. Figure 2, right shows circularly polarized light selective transmission of such chiral photonic bandgap structures for different concentration of components in CLC mixture, e.g., solid curve represents CLC mixture with 39.36% weight concentration of CB15 in E7. Figure 2, right also shows the fluorescence spectrum of CdSe QD with the center of fluorescence peak near 579 nm.

Figure, right shows an antibunching histogram of a single colloidal quantum dot in cholesteric liquid crystal bandgap structure. A dip at zero interphoton time indicates antibunching.

Figure 3. Left: Confocal fluorescence microscope image of a single CdSe quantum dot fluorescence in 1-D photonic bandgap monomeric cholesteric liquid crystal host. Right: Histogram of coincidence counts of a single CdSe quantum dot fluorescence in CLC host under pulsed excitation.
We also used nonchiral 1-D-photonic bandgap structures with defect layer doped with CdSe QDs prepared using solution processing by Prof. Menon group (Queens College, CUNY). Fluorescence maximum of these QDs is approximately at the wavelength of 620 nm. The distributed feedback microcavities were fabricated by spin coating alternating quarter wavelength thickness layers of polymers with different refractive indices (poly-vinylcarbazole (PVK) and poly-acrylic acid). Greater than 90% reflectivity was obtained using ten periods of the structure. The 1-D microcavity was formed by sandwiching a $\lambda/n$ thick defect layer with single QDs between two such Bragg reflectors. The top and bottom layers comprise 10 and 5 layers respectively. Figure 4, left shows the reflectivity of the microcavity with the cavity mode at ~ 620 nm. The quality factor (Q) of the microcavity was found to be ~ 40. The inset of Figure 4, left shows the normalized reflectivity spectra at the side of structure with 10 layers from the defect layer. Fluorescence imaging of single QDs in similar structure on our confocal microscope is shown in Figure 4, right.

**Figure 4.** Left: Reflectivity spectrum of the polymeric microcavity embedded with CdSe quantum dots. Insert: The normalized reflectivity spectrum showing the stop band of the ten-period Bragg reflector without a defect layer. Right: Single QD fluorescence imaging in a 1-D photonic bandgap polymeric microcavity under 532-nm excitation (10 $\mu$m x 10 $\mu$m scan).

**Figure 5.** Selective transmission curves for unpolarized light for 1-D chiral photonic bandgap structures in two types of liquid crystal materials. Fluorescence spectrum of prepared PbSe colloidal quantum dots with ~ 1.5 $\mu$m fluorescence max is also plotted on both figures.

Left: for Wacker liquid crystal glassy oligomer mixtures (solid-like state).
Right: for monomeric (fluid-like) liquid crystal mixtures.

For circularly polarized light a minimum transmission values of all structures will be diminished twice.
We also prepared 1-D chiral photonic bandgap structures for emitters which fluoresce at 1.5 μm. Figure 5 shows selective transmission curves for *unpolarized* light for two different types of liquid crystal materials [glassy liquid crystal crystal oligomers (solid-like) and monomers (fluid-like)].

![Figure 5](image)

**Figure 5.** Selective transmission curves for unpolarized light for two different types of liquid crystal materials [glassy liquid crystal crystal oligomers (solid-like) and monomers (fluid-like)].

Figure 6 shows PbSe quantum dot fluorescence images in a monomeric 1-D photonic bandgap cholesteric liquid crystal host.

![Figure 6](image)

**Figure 6.** PbSe quantum dot fluorescence images in a monomeric 1-D photonic bandgap cholesteric liquid crystal host.

Figure 6 shows PbSe quantum dot fluorescence images in 1-D-photonic bandgap cholesteric monomeric liquid crystal host using 40 μm x 40 μm raster scan. In spite of these quantum dot fluorescence spectrum has maximum near 1.5 μm (see Figure 5) and our experiments on detection of these quantum dot fluorescence by Princeton Lightwave 1.5 μm single photon counting receiver, Figure 6 imaging was obtained with Si SPC APD. Our suggestion is that a shorter wavelength tail of spectral distribution of these quantum dots can be in a region of a sensitivity of Si SPC APD detector. (Smaller size impurities are excluded by centrifuging).

2. **Circularly polarized fluorescence from single quantum dots in 1-D photonic bandgap cholesteric liquid-crystal hosts**

We observed for the first time a high-purity circularly polarized fluorescence from several single colloidal semiconductor quantum dots in cholesteric liquid crystal photonic bandgap liquid host (Figure 7). The degree of circular polarization is measured by the dissymmetry factor $g_c = 2(I_L - I_R)/(I_L + I_R)$. In our experiments $g_c$ reached a value of -1.6 at 575 nm. For unpolarized light $g_c = 0$.

![Figure 7](image)

**Figure 7.** Fluorescence intensity for two different circular polarization of single photons: black line – right handed, red line – left handed.
Estimation of an efficiency $P$ of polarized single-photon emission into the collecting objective provided the value of $P = 48\%$. $P$ was defined from the following relation:

$$N_{output} = N_{incmolec} \beta \alpha g Q P,$$

where $N_{output}$ is a measured number of counts/s from the APD detector, $N_{incmolec}$ is the number of photons incident on a single quantum dot, $\alpha = 0.4$ is the measured transmission of all filters, $\beta = 0.45$ is the measured transmission and collection of the objective and microscope optics, $g = 0.4$ is the QD quantum yield, and $Q = 0.58$ is quantum efficiency of the APD at 580 nm.

3. Single photon counting receivers

Prof. Sobolewski group have performed exhaustive testing of novel single-photon receivers, each based on two, fiber-coupled NbN superconducting single-photon detectors (SSPDs). The receivers can be kept without interruption for over two months inside a standard, liquid-helium transport Dewar. Thus, from an operator's point-of-view, they are room-temperature-like devices, specifically designed for quantum cryptography networks, operational at the telecom wavelength. Prof. Sobolewski group have researched a phenomenon of dark (unwanted) counts in their SSPDs and nanobridges and demonstrated the transient resistive state, causing the dark-count pulses, was due to depairing of vortex-antivortex pairs induced by the applied bias current. The dark-count rates decreased exponentially with the decrease of the bias current, as well as the operating temperature. In addition, this group have achieved a significant research progress in novel device concepts, such as detectors based on MgB$_2$ and Hg-Ba-Ca-Cu-O superconductors and ferromagnet/superconductor NiCu/Nb nanobilayer structures.

4. Research training, education and public outreach

As it was mentioned earlier, training of twelve students was accomplished during a third year of this project (see page 23 of this report). 26 undergraduate and five high-school students participated this year in a lecture-demonstration of Dr. Lukishova of a SPS setup.

A course “Quantum Optics and Quantum Information Laboratory” was continued in a 2007 Fall semester for both undergraduate and graduate students of three University Departments. Two teaching laboratory experiments were based on the single-photon source setup including antibunching measurements. Other two teaching experiments (single-photon interference in Young-double slit and Mach-Zehnder interferometers as well as entanglement and Bell’s inequality lab used different modules of single-photon generation and characterization unit (e.g., cooled EM-CCD camera and single-photon counting APDs). Figure 8. shows two students working on a single-photon interference experiments. Figure 9 shows students’ teaching laboratory results on imaging of CdSe quantum dot fluorescence.
A PI of this project Prof. Stroud actively participates in the outreach activity (see page 23 of this report for details).

5. Other group experiments on unit modules

Part of photon detection module, EM-CCD camera is practically in use almost every day both in single-photon source setup, student training and in research of other groups of the Institute of Optics.

For example, Figure 10 shows the results of using EM-CCD-camera in research of Prof. Boyd’s group on quantum lithography. Entangled photon pairs (biphoton) can increase the resolution of interference pattern by factor of 2. BBO crystal is used to generate entangled photon pairs by spontaneous parametric down conversion (SPDC) process. To obtain more biphotons, type 1 SPDC and collinear propagation conditions are used. To find exact incident beam angle to the crystal, a single photon imaging by EM-CCD camera is used. Figure 10 shows one of such images. The pump beam is slightly focused on a BBO crystal, and after that, is blocked. SPDC ring is imaged on the EM-CCD camera by a lens, and a bandpass filter (center frequency: 800 nm, bandwidth: 10 nm) is located before the CCD camera to filter out scattered light.

Figure 10. SPDC ring after type I BBO crystal (Experiment of Boyd’s group).
SPS unit was also used in research of doped cholesteric liquid crystal material fluorescence of Department of Chemical Engineering (Prof. Chen) and investigation of semiconductor colloidal quantum dots of Department of Chemistry (Prof. Krauss). Photon statistics measurement module was used in the Laboratory for Laser Energetics (Dr. Schmid and Prof. Sobolewski groups. Prof. Menon (the Queens College, CUNY) used our SPS units for testing his 1-D photonic bandgap structures doped with quantum dots.

6. Publications and conference presentations reflected the work under this award

6.1. Journal publications and periodically published conference proceedings


6.2. One-time publications in conference proceedings


6.3. Other conference lectures and presentations


