Sustainable education in the age of the second quantum revolution: fifteen years of the University of Rochester National Science Foundation supported efforts

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ABSTRACT

Quantum optics/quantum information and nano-optics educational laboratory facility (QNOL) at the University of Rochester (UR) is located within three rooms of the Institute of Optics with a total area of 587 ft^2. Four teaching labs were prepared on the generation and characterization of entangled and single (antibunched) photons demonstrating the laws of quantum mechanics: (1) entanglement and Bell's inequalities, (2) single-photon interference (Young's double slit experiment and Mach–Zehnder interferometer), (3) single-photon source I: confocal fluorescence microscopy of single nanoemitters, and (4) single-photon source II: a Hanbury Brown and Twiss setup, fluorescence antibunching. We also describe a coherent undergraduate educational program in nanoscience/nanoengineering at the UR based on the QNOL and Integrated Nanosystems Center resources. From 2006 to May 2023, a total of ~900 students have utilized the quantum/nano labs for lab report submission (including 144 Monroe Community College students) and more than 300 students have used them for lab demonstrations. These two projects have three main outcomes: (1) developing a curriculum and offering the Certificate in Nanoscience and Nanoengineering; (2) creating an exemplary model of collaboration in quantum/nanotechnology between a university with state-of-the-art, expensive experimental facilities and a nearby two-year community college; and (3) developing universally accessible "hands-on" experiments (mini-labs) on quantum/nanophotonics, learning materials, and pedagogical methods. The inexpensive mini-labs described herein can be adopted in small colleges. All developed materials and students' reports are available at http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/. Two papers in a special issue of Optical Engineering describe these two programs with more details: https://doi.org/10.1117/1.OE.61.8.081811 and https://doi.org/10.1117/1.OE.61.8.081810 .

Keywords: quantum and nanooptics undergraduate experiments, Certificate in Nanoscience and Nanoengineering, entanglement and Bell's inequality, single-photon interference, single-photon source, community college quantum technicians, quantum mini-labs

1. INTRODUCTION

This paper was presented at the symposium "How to teach quantum in the age of the second quantum revolution" (16 May 2023) https://etop.creol.ucf.edu/quantum/ during the Conference on Education and Training in Optics and Photonics ETOP 2023 (Cocoa Beach, FL, USA). It describes the design of the advanced laboratory and lecture courses on photon quantum mechanics and nanophotonics, highlighting interesting and cutting-edge experiments that can be performed in one lab period. Starting from the advanced laboratory level, quantum/nano- "mini-labs" that can be used for introductory laboratory levels both for science, technology, engineering, mathematics (STEM) majors and for nonmajors were developed. These mini-labs are universally accessible, and certain experiments may be integrated into traditional theory courses on quantum mechanics and modern physics. Although photon quantum mechanics and nanophotonics undergraduate teaching experiments have been already reported in the literature, the novelty of this study is the description of state-of-the-art experiments that can be routinely conducted in big classes, with everyday teaching of students' groups during 1.5 to 3 h of a lab time. Sturdy mini-labs experiments on recent advances of photon quantum mechanics and nanophotonics were introduced into several lectures and lab courses of different levels of students' experience, from freshman to senior, including community college students. A framework shown in Figure 1 presents all classes that used the quantum and nano-optics laboratory (QNOL) facility of the Institute of Optics, University of Rochester (UR). In upper levels QNOL classes, four basic labs address generation and characterization of entangled and single photons, demonstrating the laws of quantum mechanics: (1) entanglement and Bell's inequalities, (2) single-

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photon interference (Young's double slit experiment and Mach–Zehnder interferometer), (3) single-photon source (SPS) I: confocal microscope imaging of single-emitter fluorescence, (4) SPS II: Hanbury Brown and Twiss setup, photon antibunching. In addition, weekly lectures with theory, discussion of lab equipment, measurements results, and the history of the cornerstone experiments in quantum optics form an important aspect of the QNOL classes.

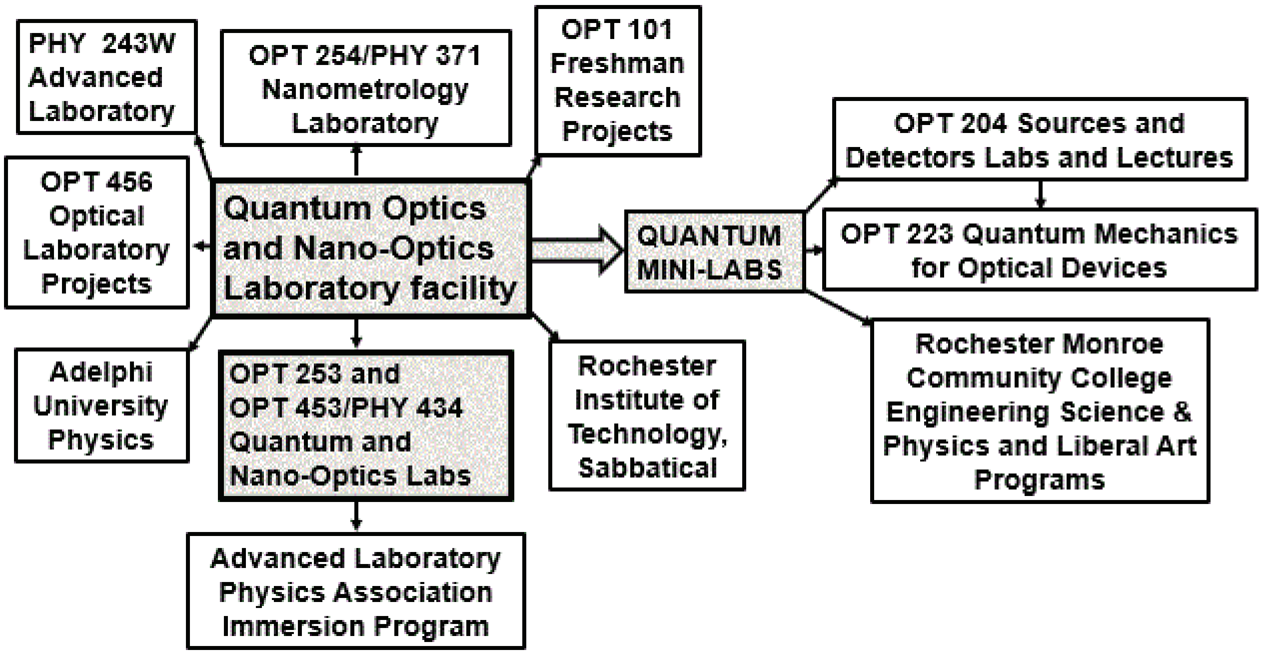


Figure 1 Diagram showing all the conducted classes based on the Quantum and Nano-Optics Laboratory facility at the Institute of Optics, UR.

This paper is organized as follows. Section 2 outlines four basic teaching lab experiments of the QNOL classes. Section 3 outlines an approach of introducing quantum/nano mini-labs to required undergraduate and graduate classes at the UR and to freshman research projects. Section 4 outlines UR program on the Certificate in Nanoscience and Nanoengineering (CNSNE). This program is based on facilities of the Institute of Optics and Integrated Nanosystems Center (URNano). Section 5 presents a discussion on teaching local Monroe Community College (MCC) students at the UR QNOL facility and URNano. Finally, Sec. 6 presents the conclusions of this study. More details on lab experiments and the Certificate program including evaluation of students' learning and references were published in two papers[1,2] of the open access special issue of Optical Engineering "Education and Training in Quantum Science and Technologies".

2. FOUR TEACHING EXPERIMENTS OF QUANTUM AND NANO-OPTICS LABORATORY CLASSES

Figure 2 shows the structure of QNOL classes OPT 253 "Quantum and Nano-Optics Laboratory" (undergraduate) and a graduate level class OPT 453/PHY 434 "Advanced Quantum and Nano-Optics Laboratory" based on four lab experiments. QNOLs are one-semester, four credit technical elective courses comprising 11 1.5- to 3.0-h lab sessions, 11 1.5-h lectures for undergraduate students, and 22 1.5-h lectures for a graduate level class; it is also popular among undergraduate students. OPT 253 has no prerequisites and students are accepted starting from sophomores. Each of the four labs hosts 2 to 4 sessions, depending on the particular lab experiment. For undergraduate students, a final grade is provided based on three lab reports written in the style of a professional paper (the last two lab reports are unified into one lab report), maintenance of each lab session's journal, five question-quizzes before each lab session, and midterm and final quizzes. For a graduate level class, two additional graded assignments are included: essays on single and entangled photon sources and 20-min oral presentations of all labs results. With ~8 to 20 students in the class, teaching assistants (TAs) supervise groups of two to four students in the labs working as a team.

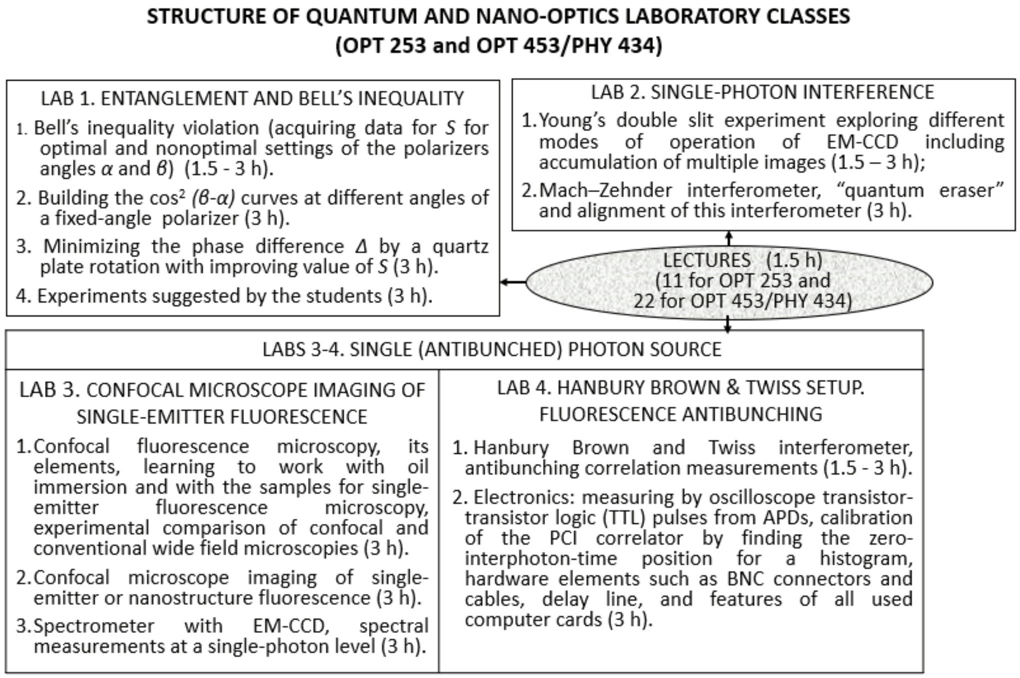


Figure 2. Structure of the QNOL classes.

2.1 Lab. 1. Entanglement and Bell's inequalities

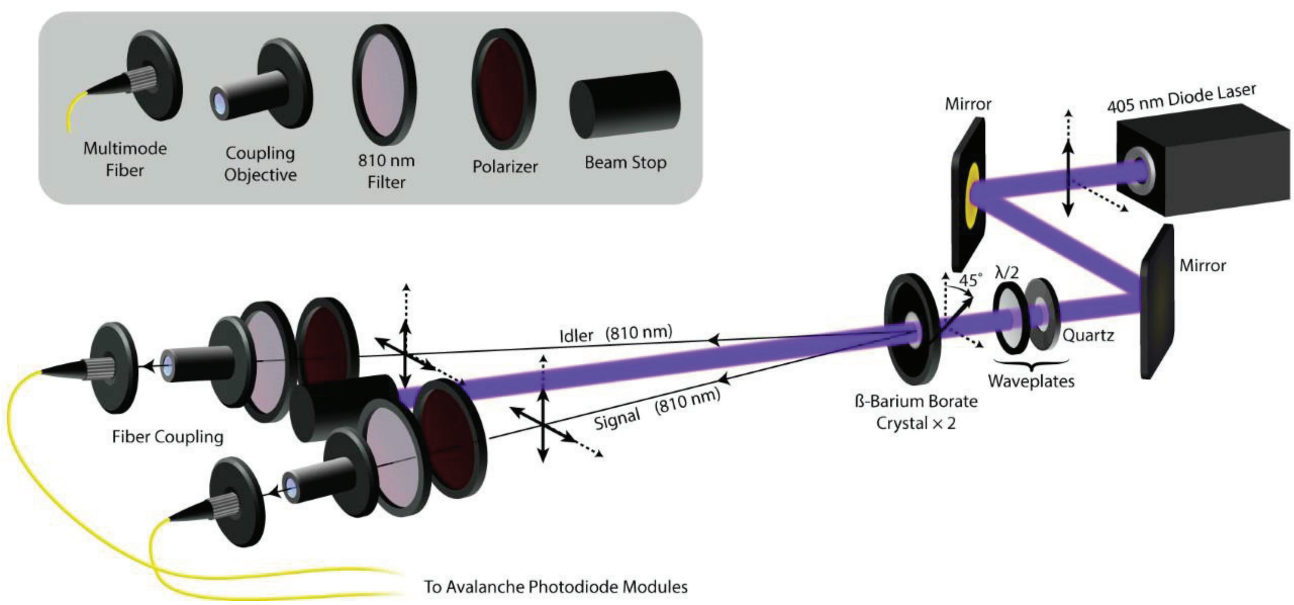


Figure 3. Schematics of an experimental setup of polarization entangled photons with two BBO crystals and a blue diode laser (prepared by R. Lopez-Rioz). Inset at the right shows one of SPDC cones (in a plane perpendicular to beam propagation direction) under argon ion laser excitation recorded by an EM-CCD camera.

The most popular approach to obtain entangled photons involves the use of a spontaneous parametric-downconversion (SPDC) process. This paper shows the sturdy lab construction on photons entangled in polarization for 1.5 to 3.0 h lab sessions (Figures 3 and 4). See more details in our paper[1]. The original experiment was implemented by Kwiat et al [3]. To learn how to build a similar setup, further details can be found in papers[4,5], our paper[1] and books[6-8]. To learn about entanglement and Bell's inequalities, the books[9-14] are recommended, and SPDC can be understood from the book by Klyshko[15]. Ref. 16 is a well-organized database of references/websites (2014) on quantum optics teaching experiments.

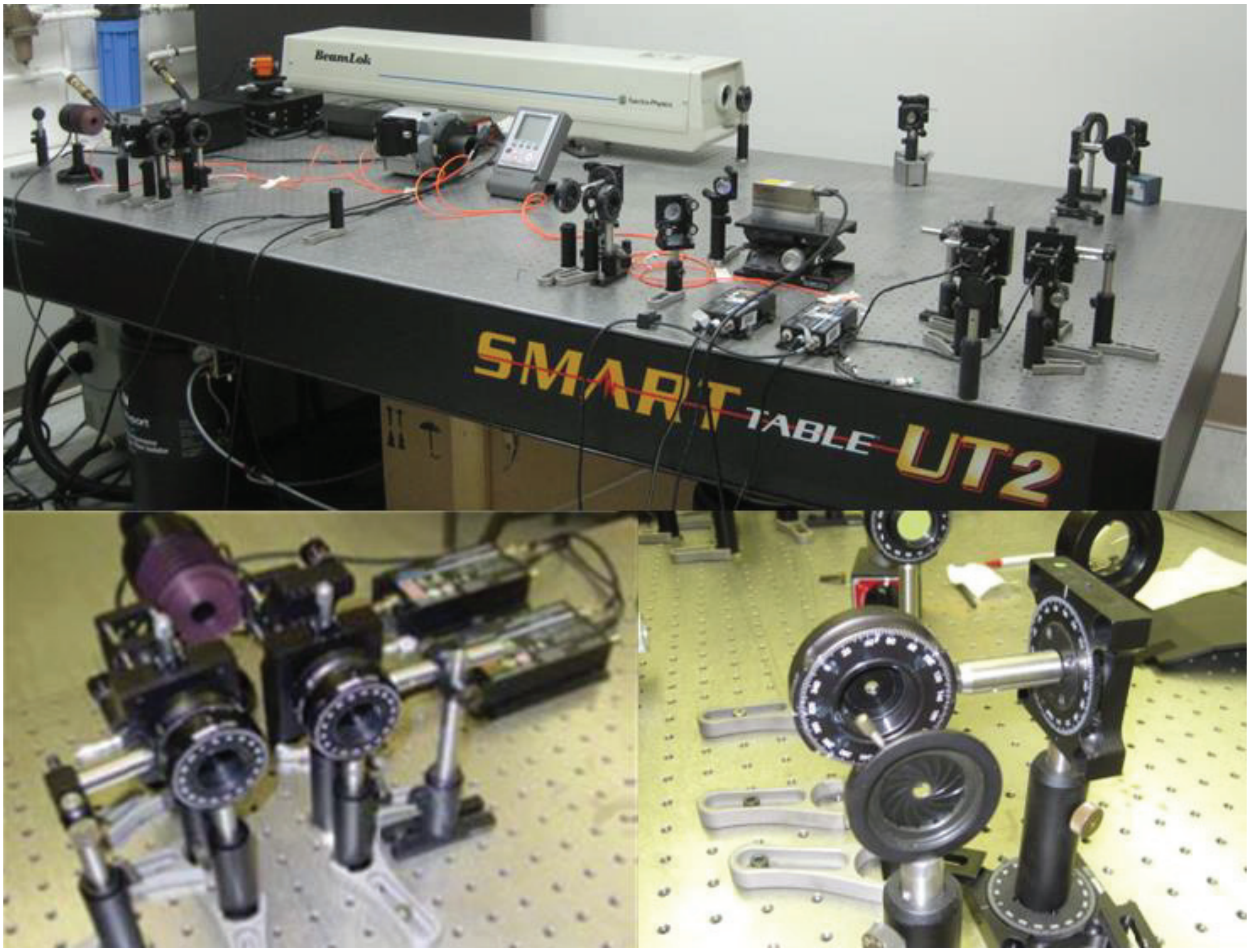
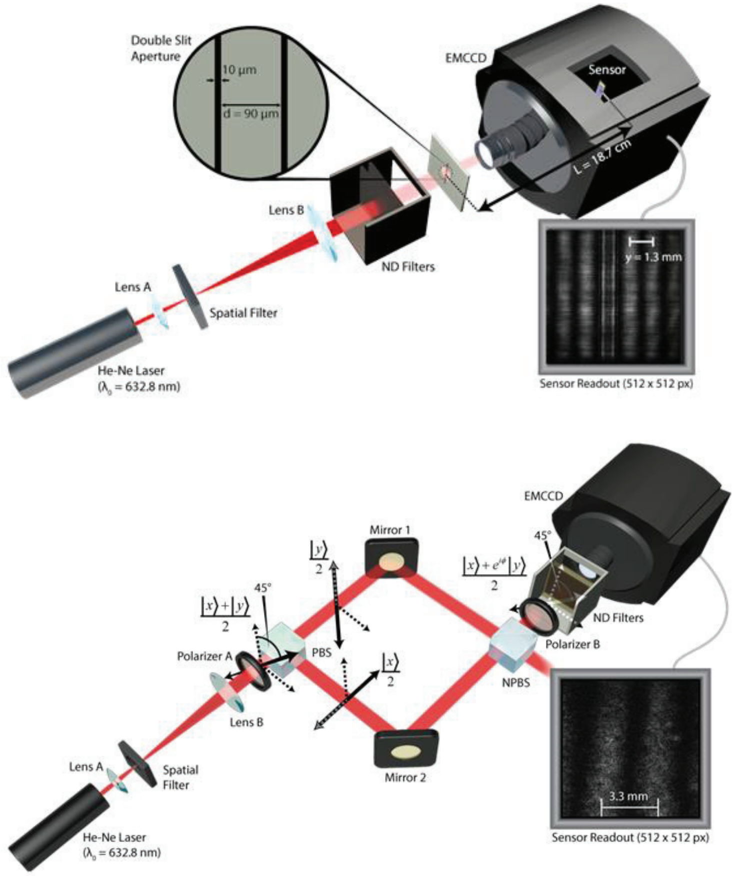
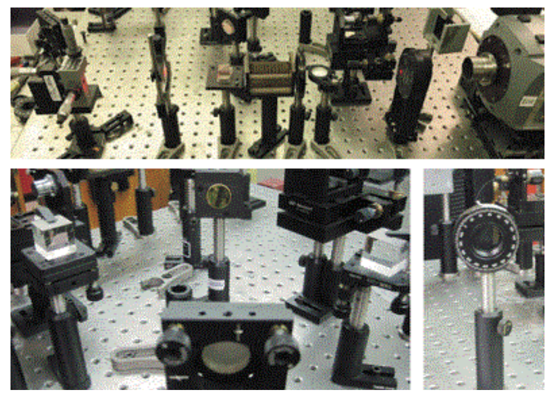


Figure 4. TOP: Two entanglement setups for the teaching labs of the Institute of Optics, UR. BOTTOM LEFT: Collection system with a three-dimensional (3-D) adjustable mount with two polarizers and APD detectors. BOTTOM RIGHT: BBO crystal set with a 3-D rotation mounting (an iris diaphragm serves for alignment).

2.2 Lab. 2. Single-photon interference (Young's double slit and Mach–Zehnder interferometers)

In this lab, wave-particle duality using an example of single photons is demonstrated (Bohr's complementarity that simultaneous observation of wave and particle behavior is prohibited by the position–momentum uncertainty relation). For this lab, an attenuated laser beam (a Poissonian light source) is a good approximation for a source of single photons, although photon antibunching (separation of all photons in time) cannot be achieved in such a source. Interference between single photons is observed in both Young's double slit and Mach–Zehnder interferometers. In a Mach–Zehnder interferometer experiment with a polarizing beamsplitter at its input, the effect of "which path" information is shown, as an inference pattern can only be acquired when that information (known linear polarization of single photons in each interferometer arm) is hidden using a 45-deg linear polarizer (quantum eraser) at an interferometer output. This laboratory provides a visual demonstration of the appearance and disappearance of interference fringes, both at laser light power, visible at room light, and single-photon levels, by carefully destroying and restoring "which-path" information using a quantum eraser in a Mach–Zehnder interferometer (further details in Refs.[1, 17–22]). Measurements are made using a He–Ne laser beam, attenuated to the single-photon level with neutral density filters. In the QNOL classes, an EM-CCD camera iXon by Andor Technologies cooled to −65°C and sensitive to single photons is used (~200 ms exposure time). It is also employed with MCC students' groups and freshman research projects. However, in classes with 40 to 50 students (a required OPT 204 class Sources and Detectors), a conventional CMOS Basler acA1920-40um USB 3.0 camera with a Sony IMX249 CMOS sensor is utilized for recording interference fringes from faint laser light attenuated for a single photon level (~1 photon per meter) but at a longer exposure time (~10 s). Figure 5 shows the schematics of two experiments of this lab: Young's double slit [Figure 5, top] and Mach–Zehnder interferometers [Figure 5, bottom]. A 40-μm slit width with a 125-μm slit separation was used in most experiments (PASCO high precision diffraction slits). Figure 6 shows the experimental setup of the Young's double slit single-photon experiment, with an EM-CCD camera as a detector (top), a Mach–Zehnder interferometer (bottom left), and a quantum eraser (bottom right). A quantum eraser experiment on dependence of fringe visibility at the Mach–Zehnder interferometer output on the angle θp of a linear polarizer (quantum eraser) is carried out.





LEFT: Figure 5. TOP: Setup of a single photon Young's double slit experiment. ND, neutral density filters; EMCCD, electron multiplying CCD camera; He–Ne, helium–neon laser. The inset at the right shows double-slit interference with a "lithographic" double slit on a glass. A fine structure is seen inside the maxima caused by interference with a reflected beam. BOTTOM: Setup for a Mach–Zehnder interferometer. PBS, polarizing beam splitter; NPBS, nonpolarizing beam splitter. The polarization vector is shown at each point of change in the system state (prepared by R. Lopez-Rios). RIGHT: Figure 6. Parts of experimental setup for single-photon interference lab (a He–Ne laser is not shown). TOP: A Young's double slit interferometer with an EM-CCD used as a detector. BOTTOM left: A Mach–Zehnder interferometer; BOTTOM right: a quantum eraser**.**

2.3 Lab 3. Single-photon source I: Confocal microscope imaging of single-emitter fluorescence

The offered QNOL courses enable students to engage in a real research environment, working on state-of-the-art, fragile, and expensive equipment used in modern quantum-optics research worldwide and that they had already used in labs 1 and 2. Every student understands the cost of each piece of equipment. In addition, in labs 3 and 4, class time was reserved for addressing "real" research questions on actual research samples or, time permitting, students prepared their own samples with single emitters that have never been investigated prior to them. Thus, this intentional blurring of the dividing line between "education" and "research" strongly increases student interest. Labs 3 and 4 serve to understanding SPS (antibunched)[23-26], a key hardware for long-distance quantum communication. To create single photons, a laser beam is focused on a single emitter that emits a single photon at a time. Single colloidal, semiconductor, nanocrystal quantum dots, and color centers in nanodiamonds were used as single emitters in these labs. Figure 7 shows the experimental setup of labs 3 and 4 as well as some students' results. A confocal fluorescence microscope with excitation by laser light of different wavelengths was used in a lab 3 for imaging and spectral evaluation of single emitter fluorescence.

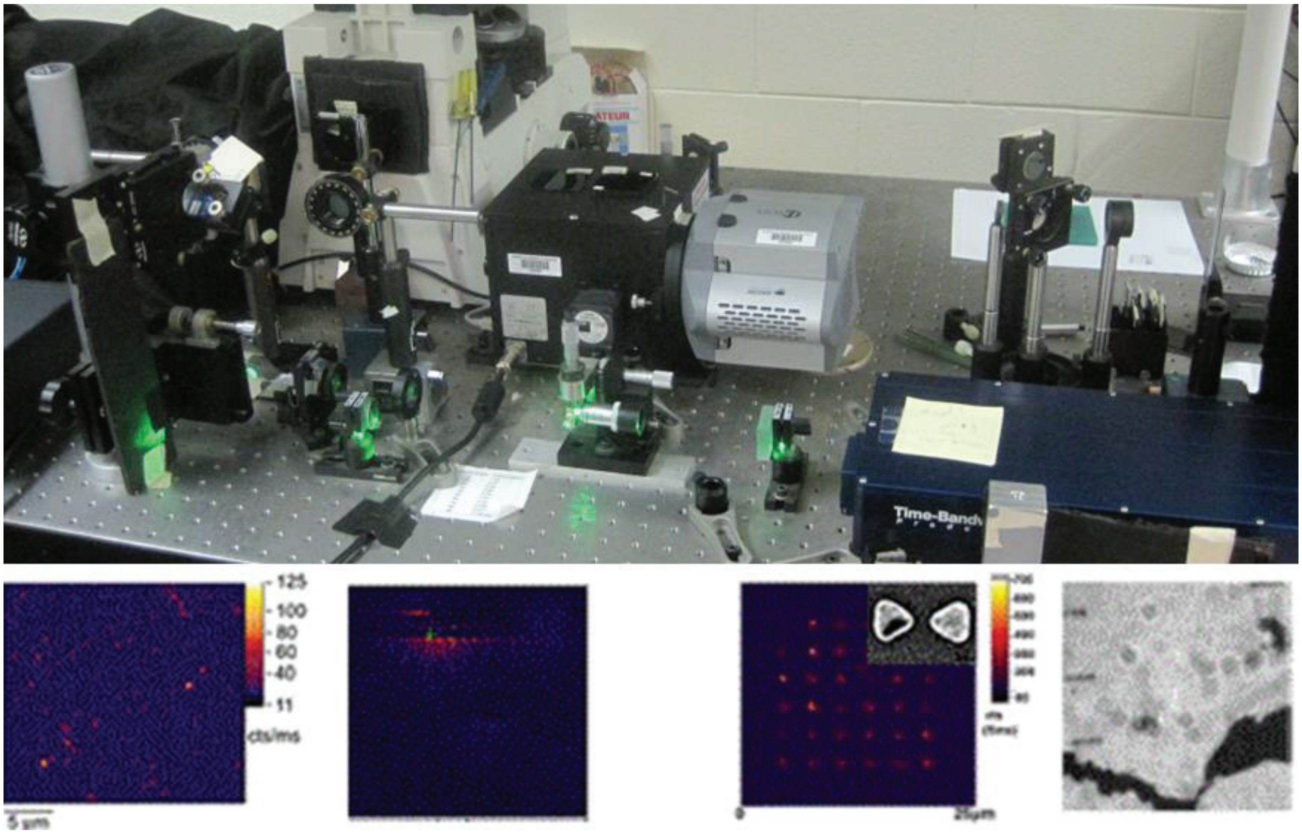


Figure 7. TOP: Confocal fluorescence microscope with a Hanbury Brown and Twiss interferometer (covered by a black tissue) and a spectrometer with an EM-CCD camera. BOTTOM: Two left micrographs: Confocal microscope imaging of single NV-centers fluorescence in 40-nm and 20-nm size nano-diamonds. The right figure of two shows blinking in fluorescence (horizontal stripes) of a single color center in a 20-nm-nanodiamond (2×2 µm raster scan). Two right images: Confocal microscope micrograph of gold photoluminescence from a bowtie nanoantenna array. Inset shows the bowtie shape of nanoantenna (SEM micrograph by Z. Shi). The right figure of two shows a wide-field sample view recorded by a CCD-camera showing a position of different nanoantenna arrays (numbers 30 to 50 nm are the value of gaps of nanoantennas located close to these numbers).

2.4 Lab. 4. Single-photon source II: Hanbury Brown and Twiss setup. Fluorescence antibunching

To prove the single-photon nature of single-emitter fluorescence (antibunching, or *all* photon separation in time), students measure time intervals between consecutive photons in lab 4. Antibunching was first obtained at the UR in 1977 by Mandel, Kimble, and Dagenais[24]. Further details can be found in Ref. 25, book 26 and review 23. For antibunching, no photons should appear at zero interphoton time. For such measurements, a Hanbury Brown and Twiss correlator[27] is used (Figure 8). It consists of a beamsplitter and two single photon counting avalanche photodetector modules (APDs). Electronic readout during students' measurements consists of a time-correlated, single-photon-counting PCI card with start and stop inputs connected to the APDs. This card (Time Harp 200, Picoquant) in conjunction with software allows to build a histogram of interphoton times. Subsequently, in the case of antibunching, a dip appears at zero interphoton time (Figure 8). While collecting the histogram data, students recorded the time traces of intermittent blinking by single emitters on a second platform. Labs 3 and 4 are connected to each other and they consist of total five ~1.5 to 3-h lab sessions (see Figure 2 for details). Following the QNOL class, students frequently continue participating in ongoing efforts on a single-photon source setup, either through independent studies or within the framework of senior projects. During final publication of results (of experiments started in the QNOL class), they become coauthors[28,29].

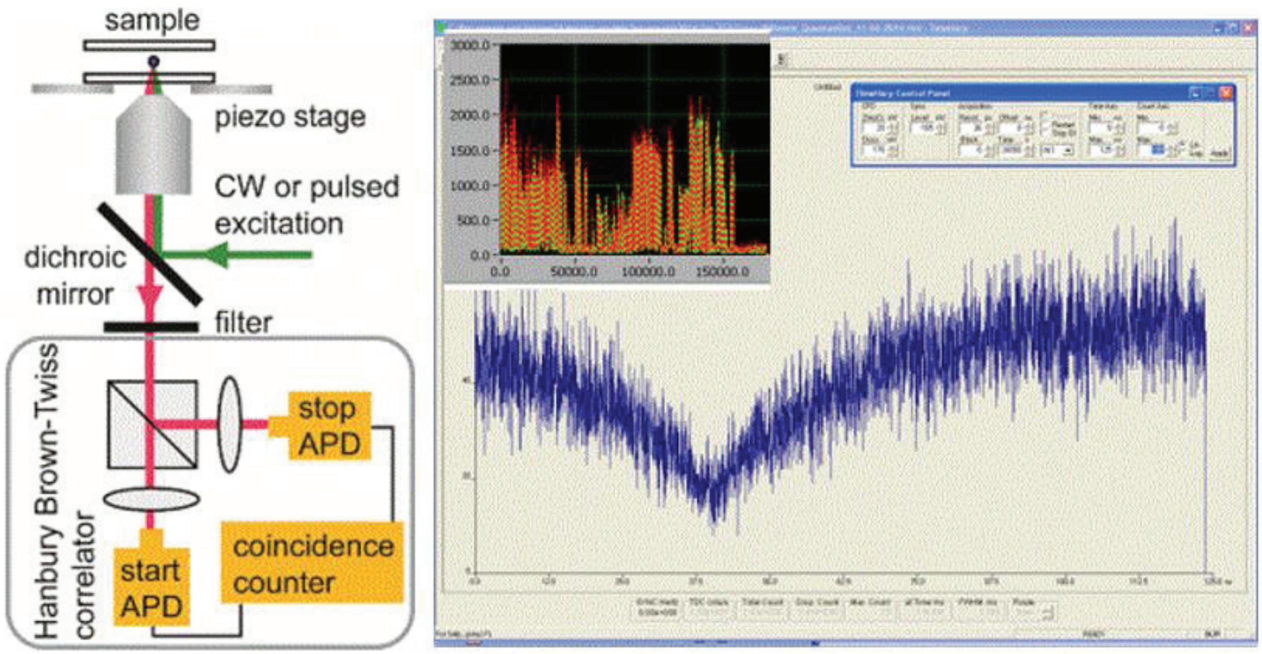


Figure 8. LEFT: Schematics of experimental setup with a confocal fluorescence microscope and a Hanbury Brown and Twiss correlator (prepared by L. Bissell). RIGHT: Raw data histogram of interphoton times with a dip at zero interphoton time indicating photon antibunching. Fluorescence of CdSeTe nanocrystal quantum dots inside a gap of a bowtie nanoantenna was studied. Inset shows a time trace of this quantum dot fluorescence with blinking.

3. MINI-LABS ON QUANTUM OPTICS AND NANOPHOTONICS IN REQUIRED UR CLASSES

Short, 3-h mini-labs were introduced into several other UR classes. For instance, in a required lecture class Quantum Mechanics for Optical Devices (OPT 223), taught by C. Stroud for juniors and seniors, 3-h versions of entanglement and single-photon interference labs of QNOL were introduced (see Labs 1 and 2 in previous section). Consequently, the success of this approach further facilitated the inclusion of two 3-h quantum labs to specifically created required labs and lecture class Sources and Detectors (OPT 204) for juniors and seniors taught by the author. OPT 204 is a complimentary class to two required lecture classes, with one being "quantum" OPT 223. In the OPT 204 class, a single-photon interference lab (Lab 2 in previous section) with a conventional CMOS camera as a detector is included. Three other mini-labs that can be easily reproduced are described below. Freshman OPT 101 quantum research projects, taught by W. Knox and T. Brown are also carried out on the QNOL facility.

3.1 Photon statistics measurements from Poissonian and pseudothermal sources

This OPT 204 lab was developed by N. Vamivakas from the experiment described in Ref. 30. See details of this lab in Ref. 2. In this experiment, students familiarize themselves with photon counting by measuring a Poissonian photon statistics from a laser light attenuated to a single-photon level and Bose–Einstein statistics from a pseudothermal source created using a rotating ground glass in a laser beam. Figure 9, left shows this experimental setup and some results.

3.2 Calculation of sizes of CdSe nanocrystal quantum dots from spectral measurements

One more quantum/nano, 15-min mini-lab on using Schrödinger equation for calculation of sizes of CdSe nanocrystal quantum dots from spectral measurements is included into the OPT 204 class. This lab is discussed in detail in Sec. 4.1 of our paper[2]. Figure 9, right shows fluorescence of quantum dot solutions under ultraviolet (UV) irradiation as well as its spectrum recorded by the Ocean Optics spectrometer through an optical fiber.

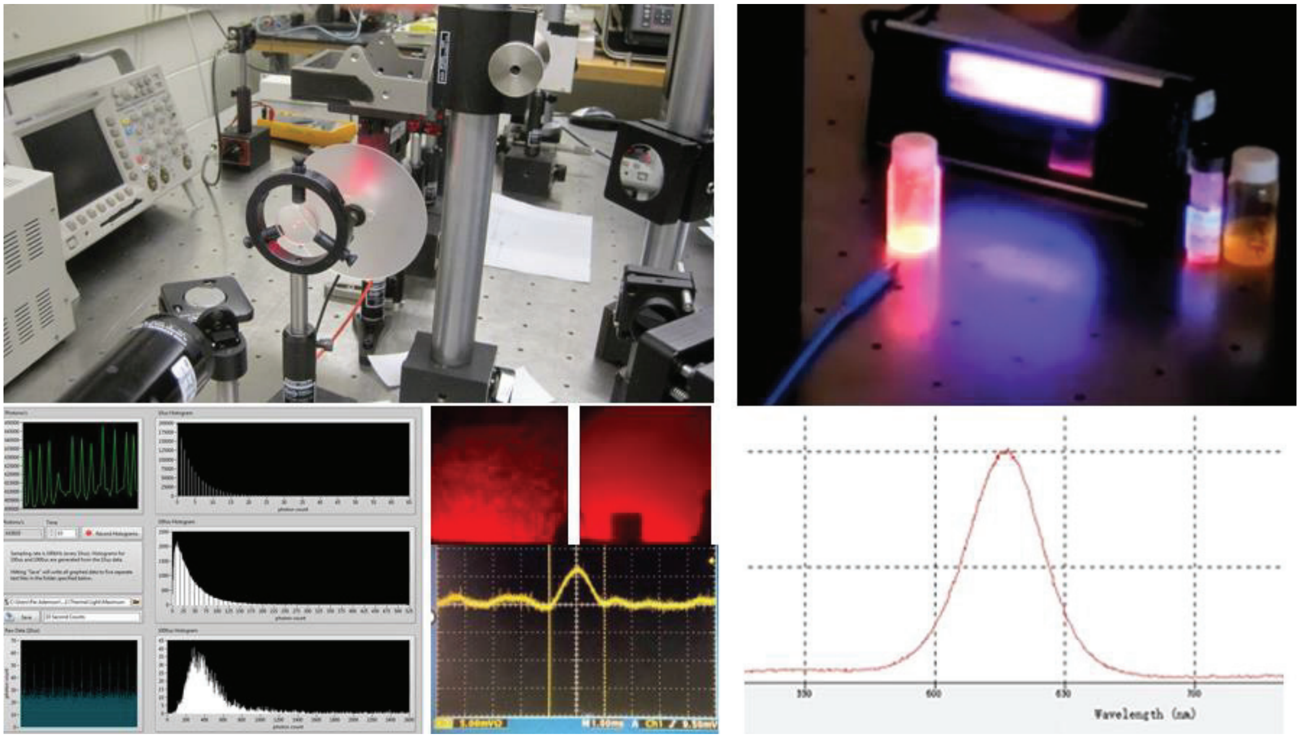


Figure 9. Two OPT 204 class quantum mini-labs[2] (not included to QNOL classes). TOP LEFT: Setup of a 3-h mini-lab session on a pseudothermal source with a rotating ground glass. BOTTOM LEFT: User interface of a LabView software showing photon statistics changes for data collected with different time bins [less or longer than a coherence time (see a provided oscillogram)]. Two laser beam cross sections show speckles at the output of a still ground glass (Poisson statistics) and speckles disappearance with a ground glass rotation. TOP RIGHT: Setup of a 15-min mini-lab session on using Schrödinger equation for calculation of sizes of CdSe nanocrystal quantum dots from spectral measurements. Vials with quantum dot solutions fluoresce under UV source illumination. A spectrometer fiber input is seen at the left. BOTTOM RIGHT: Fluorescence spectrum from a quantum dot solution recorded by a fiber-optics spectrometer.

3.3 Cholesteric liquid crystals photonic bandgap structures

Planar alignment of cholesteric liquid crystal (CLC) materials is among the simplest methods for the preparation of photonic bandgap structures. They can be prepared from a cholesteric oligomeric powder by heating the powder between two cover-glass slips on a hotplate (~70°C to 100°C) to the liquid state. In this liquid state, the cholesteric material is sheared between substrates for planar alignment. Once cooled to a glassy (solid) state, the liquid crystal alignment remains preserved. Attractive colors appear from the initially uncolored powder oligomers, indicating photonic bandgap (selective reflection) structures. Using a monomeric (fluid form at room temperature) CLC, the preparation of a photonic bandgap requires only 1 min. A drop of a monomeric, cholesteric liquid crystal should be placed between two glass slips; after shearing, a uniform color from an initial milky liquid crystal appears. See details in Ref. 2.

This lab was very popular among middle and high school students and their parents during the Institute of Optics Family Day. OPT 204 students measured the reflectivity of the prepared CLC photonic bandgap structures during their lab on spectroscopy of different light sources and radiometry using a Konica Minolta CM-3700 A spectrophotometer with an integrating sphere. Liquid crystal examples were used in an OPT 204 lecture workshop on nonclassical light sources[31-33]. Entangled sources, indistinguishable photons, and a Hong-Ou-Mandel interferometer[34,35] were described, and examples of experiments with liquid crystal structures in a Hong-Ou-Mandel interferometer at the Institute of Optics were discussed[36-39].

4. UR PROGRAM ON CERTIFICATE IN NANOSCIENCE AND NANOENGINEERING FOR UNDERGRADUATE STUDENTS

Since 2015, 48 undergraduate students from different UR departments (40 students from optics, three students from biomedical engineering, one student from chemical engineering, one student from mechanical engineering, one student from physics, one student from the IDE program, and one foreign university student) completed the program on CNSNE by May 2023. Forty of them completed the program after ending the NSF grant. Before describing the details of the program, we present the results of our study on career paths after graduation. We followed the career paths of the 36 awardees as of May 2021. Figure 10 shows that 50% of the 36 awardees selected nanoscience/nanotechnology careers [the right data bar (orange color)], 50% of all awardees stayed in academia (graduate students), ~41.7% selected business, one student selected the US Navy, one student went to the National Laboratory. From the awardees in academia, 60% are working on projects connected with nanoscience/nanotechnology, and 40% of awardees in business are working in nanotechnological companies. The CNSNE program has the following requirements for completion (see Figure 11): (1). A required four credit-hour laboratory course OPT 254/PHY 371 "Nanometrology Laboratory." This course started in the spring of 2015 and was specifically prepared for this program. (2). The students' selection should contain two other courses with nanotechnology content (refer to the list of possible courses shown in Figure 11). (3). A full-semester research or design project related to nanoscience or nanotechnology. The Institute of Optics administration, the Dean's office of the Hajim School of Engineering and Applied Sciences, and the UR Laboratory for Laser Energetics financially supported this program.

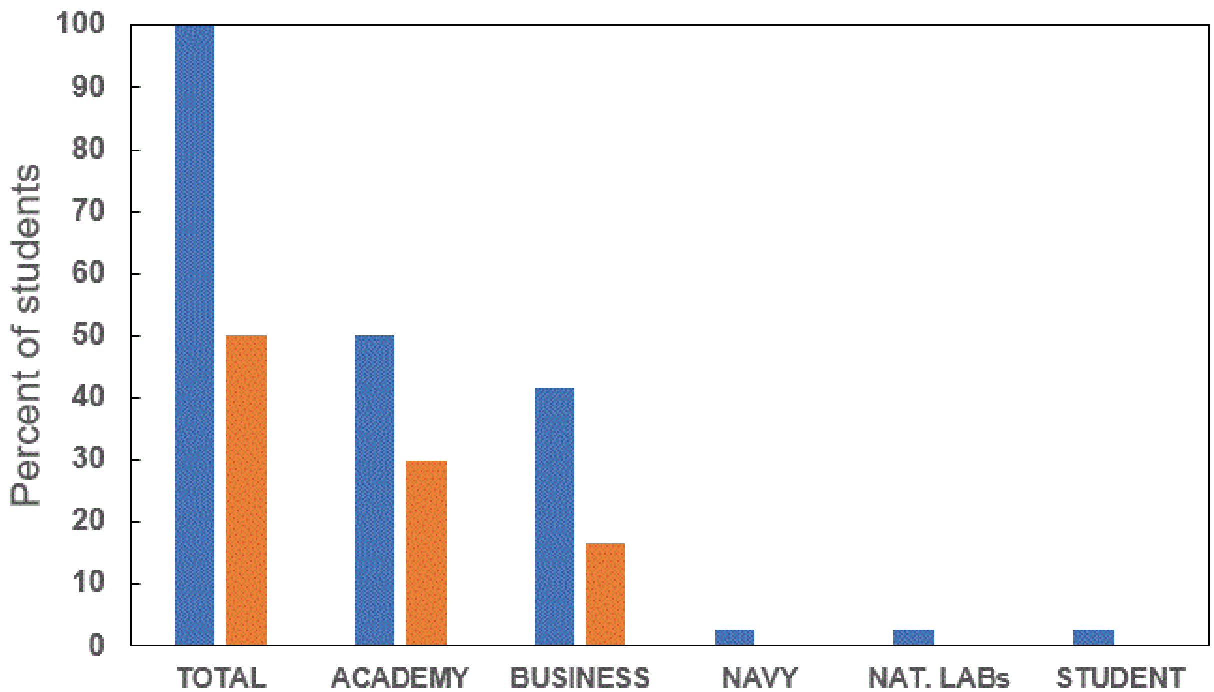


Figure 10. Histogram showing career selection of the CNSNE awarded students (graduated by May 2021). The right bar (orange color) indicates a percent of students working in nanoscience/ nanotechnology.

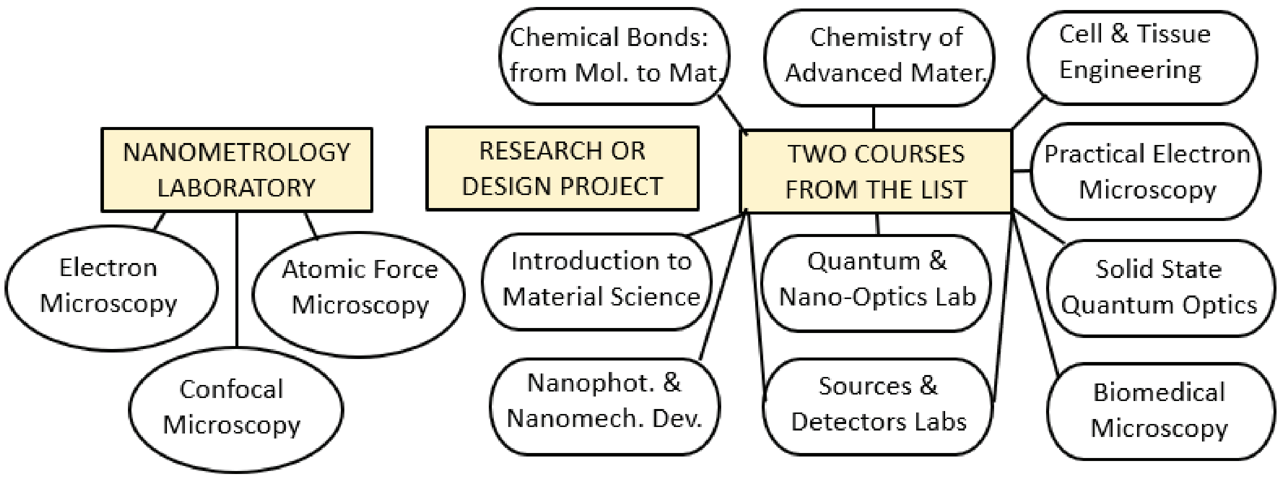


Figure 11. Requirements for the program on the CNSNE.

2.1 Required Nanometrology Laboratory class (OPT 254/PHY 371)

The prerequisite class for the Certificate, Nanometrology Laboratory OPT 254/PHY 371, quickly became popular: the electron microscope limited the maximum number of students from six to eight students. The instruction proceeds entirely through direct student-professor contact at all times. Three-course modules were taught by three instructors: (1) electron microscopy [scanning electron microscopy (SEM) and transmission electron microscopy (TEM)], McIntyre (now O'Neil) and Lukishova; (2) optical microscopy (wide-field and confocal fluorescence microscopy of single nanoemitters), nanoobjects/nanoengineering/quantum nanophotonics, Lukishova; and (3) atomic force microscopy (AFM) (started by Papernov and continued by Lukishova). The electron microscopy module consists of (1) six 1.5-h lectures and two 2 to 3-h labs (SEM and TEM), (2) the optical microscopy module includes five 1.5-h lectures and four 1.5-h labs, and (3) the AFM module contains two 1.5-h lectures and three 1.5-h labs. Throughout the semester, students face three exams (in each module separately) and are required to submit individual lab reports for each module (during the pandemic years, students submitted an essay on electron microscopy instead of a lab report).

2.2 Undergraduate research and design projects

The scientific direction of research topics for CNSNE depends on a specific department. UR is a top research university with professors leading cutting-edge projects; therefore, all students working toward their certificates are members of strong scientific groups. Design projects are created based on industry demands to solve technological problems of companies. For design projects, students working in groups of three to four have two advisors: a company representative (primary customer) and a UR faculty member. During the two-semester project, students regularly communicate with primary customers, although the design projects are conducted at the UR. In addition, all design and senior thesis projects are discussed and graded in a separate class, OPT 320/321 Senior Design and Senior Thesis (Professor Knox), which includes more than CNSNE projects. After this class, students submit reports, deliver talks, and present posters on UR Senior Design Day.

5. TRAINING LOCAL MONROE COMMUNITY COLLEGE STUDENTS AT THE UR

This section describes the joint efforts of UR and MCC in forging an exemplary model of collaboration between a research university with strong programs in science and technology and modern experimental facilities and a local two-year CC. One of the challenges faced by physics courses at CCs is the lack of student activities in modern experiments. A typical lab consists predominantly of replicating nearly 100-year-old experiments (photoelectric effect, hydrogen spectroscopy, etc.). The addition of state-of-the-art lab experience makes the course truly modern and provides a strong motivating force for future STEM studies. Experience at the QNOL facility and URnano enhanced the laboratory portion of MCC's modern physics course, helping prepare MCC students for employment and making it easier for students enrolled in the 2 + 2 transfer option. In addition, liberal arts students taking the MCC Physics for non-majors course enlivened a broader outreach.

From 2009 to 2015, 92 MCC students (both from STEM majors and nonmajors) participated in labs at the UR QNOL facility. MCC students participated in 3-h sturdy mini-labs on (1) entanglement and Bell's inequalities and (2) single-photon interference with a single-photon-counting, EM-CCD camera. MCC professor P. D'Alessandris was instructed in the use of the EM-CCD camera, to teach his MCC students the single-photon interference lab at the UR. The author of this paper (Lukishova) taught to MCC students entanglement and Bell's inequality lab. Within this collaboration supported by three NSF grants, lab manuals were specifically rewritten for MCC students.

The fourth NSF grant (NUE) strengthened the UR–MCC collaboration. During 2014–2015, other 52 MCC students conducted two 3-h labs at the UR [atomic force microscopy of nanodiamonds (Lukishova) and photolithography in a clean room (McIntyre), see Figure 12]. Professor P. D'Alessandris led the project for the MCC as well. After completing the lab activities, the MCC students answered conceptual and quantitative questions about the experiments prepared by Prof. D'Alessandris using UR manuals and quizzes.

Figure 12. LEFT: MCC and UR logos prepared by MCC students using photolithography and vacuum deposition of a metal. RIGHT: One group of MCC students in the UR clean-room garments near the entrance to the clean room.

6. CONCLUSION

We are in the midst of a second quantum revolution, which will be responsible for most of the key physical technological advances for the 21st century. Many countries around the world have national programs on quantum science and technology. The arrival of the new fields of quantum optics, quantum computation, and quantum communications and the rapid progress in photon-counting instrumentation present new opportunities for teaching the most difficult concepts of quantum mechanics using a set of simple, easily understandable, and exciting experiments with single and entangled photons. The modern reality is that high-school students already know about entanglement and some of them violate Bell's inequality at their home setup; for instance, see Ref. 6.

The goal of this paper is to share 15 years of experience of the Institute of Optics, UR, in preparing every optics student to a second quantum revolution. We introduced sturdy quantum optics lab experiments to classes from freshman to senior and graduate student levels, so every UR optics student learns quantum optics concepts in practice by doing lab experiments with photon counting instrumentation. We increased the diversity of involved students by collaborating with a local community college and bringing its students to the UR to carry out 3-h quantum/nano mini-labs at the UR. This paper provides a description of universally accessible quantum/nano optics experiments that can be introduced into either a separate advanced lab class on quantum/nano optics or lab or lecture classes with a large number of students. These quantum mini-labs are based on the upper-level, advanced laboratory, whole semester QNOL class with 11 lab sessions (see Figure 2). Our methods and lab experiments can be adopted by other universities and colleges.

The main achievements of our NSF supported activities are (see details in Refs. 1 and 2):

- from 2006 to May 2023, more than 900 students have utilized quantum/nano labs (including 144 MCC students) and approximately 300 students have used them for lab demonstrations.
- initially supported by NSF, the program on the Certificate in Nanoscience and Nanoengineering issued certificates to 48 students (by May 2023).
- creating a *reproducible* model of collaboration in quantum and nano- technologies' education between a university with state-of-the-art, expensive experimental facilities, and a nearby, two-year community college with participation of the local community college. 52 MCC students carried out two labs at the UR on the AFM and a photolithography in a clean room; and 92 MCC students – two "quantum" labs on entanglement and single-photon interference using state-of-the-art photon counting instrumentation.
- developing universally accessible hands-on experiments on quantum and nanophotonics ("MINI-LABS"), learning materials and pedagogical methods to educate students with *diverse* backgrounds, including freshmen and non-STEM-major community college students. These 1.5-3 h minilabs were introduced in some Institute of Optics required classes.

During QNOL classes the history of discoveries of most important experiments is included in the lecture materials. The undergraduate students learn that the first experiment on a feeble light interference was carried out in 1909 by Sir G.I. Taylor[40] when he was an undergraduate student. Students also learn that Young's double slit experiment had a tremendous influence on the history of science, and it continues to inspire and direct modern researchers to use it and its modifications (e.g., Mach–Zehnder interferometer) to probe new areas of physics[41]. In addition, a history of discovery of a Hanbury Brown and Twiss effect was discussed[42]. Students also learn from the lecture that the human eye is sensitive to a few photons[43,44], and even the Nobel Prize in Physics (1958) was awarded for observation by Cherenkov of a feeble cone of Vavilov-Cherenkov radiation (1934) after accommodation of his eyes to darkness[43].

Lab manuals, lab reports, conference presentations and other materials are located on the QNOL and CNSNE website http://www2.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/ .

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