15 Years of Quantum Optics Educational Facility at the Institute of Optics, University of Rochester

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Abstract: Educational laboratory facility on single and entangled photons located in three separate rooms of the Institute of Optics with total 587 sq. ft. was used for teaching several classes of diverse students during 15 years.

1. Introduction

At the Institute of Optics, University of Rochester (UR), we have adapted to the main challenge (the lack of space in the curriculum) by developing a series of modular 3-hour experiments and 20-min-demonstrations based on technical elective, 4-credit-hour laboratory course "Quantum Optics and Nano-Optics Laboratory" (OPT 253/OPT453/PHY434), that were incorporated into a number of required courses ranging from freshman to senior level [1]. Since 2006 up to May 2021, more than 800 students passed through the labs with lab reports submission (including students of Rochester Monroe Community College) and more than 250 students through lab demonstrations. This facility and its program were supported by four National Science Foundation grants [1].

2. Basic Class "Quantum and Nano-Optics Laboratory"

In a basic undergraduate class OPT 253 and its graduate version OPT 453/PHY434 (with additional assignments), four teaching labs were prepared on generation and characterization of entangled and single (antibunched) photons:

(1) *Entanglement and Bell's inequalities* (Figure 1, top left);

(2) *Single-photon interference* (Young's double slit and Mach-Zehnder interferometers) (Figure 1, bottom);

(3) *Single-photon source I*: confocal microscope imaging of single-emitter (colloidal nanocrystal quantum dots and NV-center nanodiamonds) fluorescence in photonic or plasmonic nanostructures (Figure 1, top right).

(4) *Single-photon source II*: Hanbury Brown and Twiss setup. Fluorescence antibunching from nanoemitters.

Manuals, students' reports, presentations, lecture materials and quizzes starting from year 2006, as well as some NSF grants' reports are placed on a website http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/ .

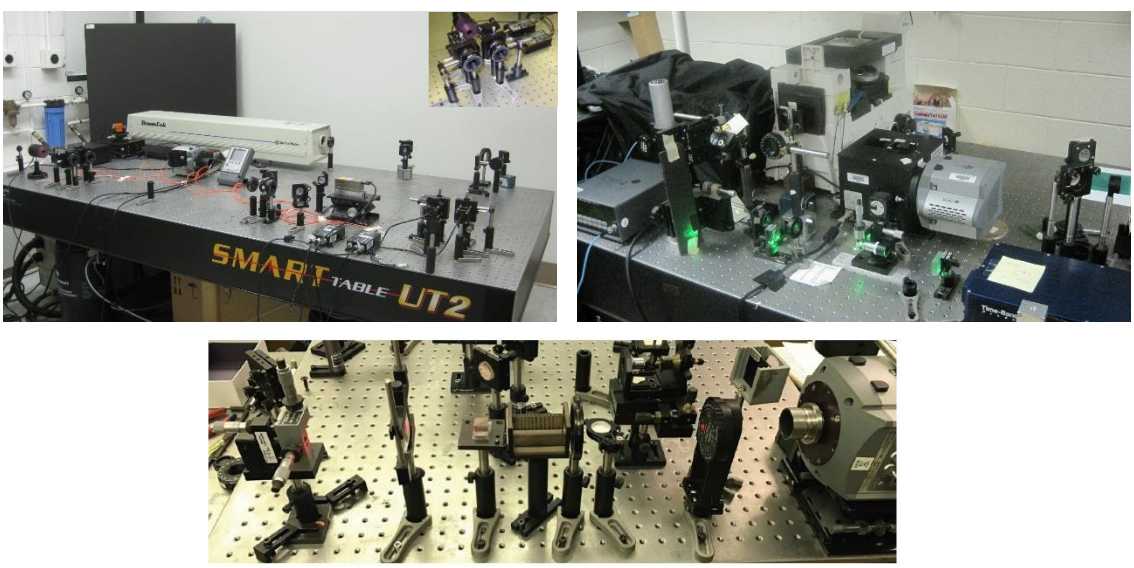

Figure 1. Photos of different experimental setups of the Quantum Optics educational facility. TOP LEFT: Entanglement and Bell's inequalities setup (insert in a top right corner shows two linear polarizers, a collection system for entangled photons, and two single-photon counting detectors).TOP RIGHT: A generation and characterization unit for single (antibunched) photons. BOTTOM: A part of a single-photon interference experiment with an electron-multiplying (EM) CCD camera (a Young's double-slit setup).

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3. Introduction of Mini-Labs on Quantum Optics to Other Classes

Figure 2. Photos of two experiments of the OPT 204 lab class. LEFT (from a Zoom video recorded in 2021 for remote students): Calculation of sizes of colloidal nanocrystal quantum dots from spectral measurements using Schrödinger equation. RIGHT: Photon statistics measurements from a pseudothermal source.

A short, three-hour lab versions of "quantum" labs from the OPT 253 class were developed for the students with diverse backgrounds. Some new experiments in quantum optics were introduced as well. For instance, for a required OPT 204 lab class for juniors/seniors Sources and Detectors, a single-photon interference lab from OPT 253 was included, but in stead of a EM-CCD as a detector, a CMOS camera was successfully used. In two other labs of this OPT 204 class two new quantum optics experiments were introduced (see Figure 2): (1) Calculation of sizes of colloidal nanocrystal quantum dots from spectral measurements using Schrödinger equation (Figure 2, left), and (2) Photon statistics measurements from a pseudothermal source and a laser.

4. Freshmen Research Projects

It became a tradition, that every year freshmen from the OPT 101 class "Introduction to Optics" of Wayne Knox and later of Thomas Brown use "quantum" facility for their research projects. One year (2010) 16 freshmen from different departments were attracted by the word "quantum". Three freshmen groups with three different ten-hours projects on fragile equipment were led by three experienced quantum optics Ph.D. students. Even during a Pandemic (Fall 2020) OPT 101 students carried out their project on entanglement and Bell's inequalities.

5. Dissemination of Results to Other Universities

- The NSF grants supported teaching Rochester Monroe Community College (MCC) students in quantum optics and nano-optics laboratory at the UR. During a decade of NSF support, 144 MCC students with their professor Paul D'Alessandris visited the UR for two three-hour labs. On the "quantum" facility, MCC students learned entanglement and Bell's inequalities, single-photon interference, and atomic force microscopy. They also worked in a clean-room on photolithography under the supervision of Brian McIntyre.
- Rochester Institute of Technology (RIT) was our collaborator in one of the NSF-supported educational projects. During Fall 2009, Ron Jodoin from RIT spent his sabbatical in UR "quantum" labs. Later RIT established their own quantum-optics teaching lab facility learning UR experience.
- In August 2011, UR participated in the Immersion Program of the Advanced Laboratory Physics Association (ALPhA) and hosted six visitors from different universities for 3 days, familiarizing them with UR lab-course experience on photon quantum mechanics.
- During two days (October 2012), 5 students of Adelphi University and their professor Sean Bentley (Ph.D. from the Institute of Optics) carried out four labs at UR "quantum" facility.
- Several students' groups from the UR, Colgate University, and Alfred University visited "quantum" facility for lab demonstrations.

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References:

[1] S.G. Lukishova, "Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: teaching quantum mechanics and nano-physics with photon counting instrumentation", Paper 100-189, 14th International Conference on Education and Training in Optics & Photonics (ETOP), May 29-31, 2017, Hangzhou, China.