10. Quantum Optics Laboratory

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Approval of the National Quantum Initiative Act establishes a federal program to accelerate quantum research and development for the United States' economic and national security, which also includes training quantum engineers.

Quantum Optics, Quantum Information, and Nano-Optics Educational Laboratory Facility at The Institute of Optics: Some History

The first quantum optics, quantum information, and nano-optics research and educational laboratory facility at The Institute of Optics was built in 2005. Initial equipment for the entanglement and Bell's inequality experiment was borrowed from Lucas Novotny. Graduate student Anand Kumar Jha (now a quantum optics professor) assembled this setup. Other labs were based on my research facility on single-photon generation and characterization funded by Army Research Office (ARO) and National Science Foundation (NSF) grants.[1] In 2006, a four-credit-hour quantum optics advanced laboratory course for both undergraduate and graduate students appeared in The Institute of Optics curriculum.

A new step was started from support of Carlos Stroud, a director of the Center for Quantum Information, and two NSF educational grants of 2007–12. Wayne Knox's and Per Adamson's help, a donation from Spectra Physics, and a Kauffman foundation Initiative Award permitted further development of this facility. Now it is located in three rooms in Wilmot with a total of 587 square feet. The courses Quantum Optics (OPT 253) and Nano-Optics Laboratory (OPT 453/PHY 434) became popular among the students.[2] Some of the students of the OPT 253 class went on to become quantum optics professors (Mehul Malik, Zhimin Shi, Omar Magaña-Loaiza, and Heedeuk Shin).

Currently these courses consist of ten lectures and four six-to-fifteen-hour labs: (1) entanglement and Bell's inequalities; (2) single-photon interference (Young's double slit experiment and Mach-Zehnder interferometer) and quantum eraser;

(3) single-photon source I: confocal microscope imaging of single-emitter fluorescence; and (4) single-photon source II: Hanbury Brown and Twiss setup and photon antibunching.[3] These labs with different requirements for graduate and undergraduate levels are in constant development. For instance, the Wadsworth C. Sykes Faculty Engineering Award of the Hajim School permitted a very enthusiastic teaching assistant, Joe Choi, to build a new entanglement setup. Joe Choi as well as Anand Kumar Jha were very creative, occasionally insisting with energy and passion on including some measurements that were not previously planned. Lucas Novotny and his group, especially his postdoc Andreas Lieb, were very helpful. Luke Bissell, a PhD student, also contributed to this class.

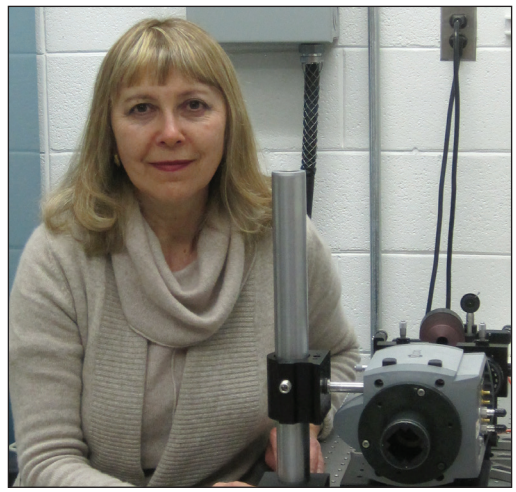

Figure 10.1. Svetlana G. Lukishova with the EM-CCD camera for single-photon experiments.

One strength of this course is the students' immersion in a real research environment, working on state-of-the-art, fragile, and expensive equipment that modern quantum optics research uses around the globe. Occasionally in the class students obtained results that were reported later at the top professional conferences or included in journal publications. This intentional blurring of the dividing line between "education" and "research" strongly boosts student interest.

Short, three-hour lab versions of the quantum labs were developed for students with diverse backgrounds. More than 560 students of the University of Rochester carried out different versions of these labs (from 2006 to Fall 2019), which were included to the following classes:

1. First-year: It became a tradition that, every year, freshmen from the OPT 101 class of Wayne Knox and later of Thomas Brown use the "quantum" facility for their ten-hour research projects.
2. Juniors and Seniors: In another class, Quantum Mechanics for Optical Devices (OPT 223), taught by Carlos Stroud, three-hour versions of entanglement and single-photon interference labs were introduced. The last lab was also included in the Sources and Detectors (OPT 204) labs.
3. Graduate class: "Quantum" projects of Optical Laboratory (OPT 456) are based on this facility.
4. Department of Physics and Astronomy: An entanglement lab at The Institute of Optics also became popular among physics students of the Advanced Laboratory (PHY 243W)

Figure 10.2. Students of Fall 2016 class OPT 253/OPT 453 on the lab lecture.

Program on the Certificate in Nanoscience and Nanoengineering

In 2015, the quantum optics, quantum information, and nano-optics lab facility became the basis for the undergraduate program on the Certificate in Nanoscience and Nanoengineering, suggested by Nick Bigelow, a director of the Integrated Nanosystems Center (URnano).[4] This program was supported by an NSF grant. From 2015 to May 2019, thirty-four students were awarded the certificate after taking two classes on nanoscience/nanotechnology, carrying out a one semester research or design project in this field, and taking a new class Nanometrology Laboratory (OPT 254/PHY 371), taught by Brian McIntyre, Semyon Papernov, and Svetlana Lukishova. This class consists of three lab modules on microscopies: (1) electron (SEM and TEM), (2) atomic force, and (3) confocal fluorescence.

Dissemination of Quantum and Nano-Optics Labs among Other Institutions

NSF grants supported teaching Monroe Community College (MCC) students in the quantum optics and nano-optics laboratory and in URnano at the University of Rochester. During a decade of NSF support, 144 MCC students with their professor Paul D'Alessandris visited the Wilmot Building for two three-hour "quantum" or "nano" labs. Brian McIntyre taught MCC students at URnano.

During Fall 2009, Ron Jodoin from the Rochester Institute of Technology spent his sabbatical in the quantum labs of The Institute of Optics. In August 2011, The Institute participated in the Immersion Program of the Advanced Laboratory Physics Association and hosted six visitors from different universities for three days.[5] During two days in October 2012, five students of Adelphi University and their professor Sean Bentley (PhD, The Institute of Optics) carried out four labs at this facility. Experience in the quantum optics labs was also shared with the University of Oklahoma–Tulsa. Several student groups (more than 250 students) from the University of Rochester, Colgate, and Alfred University visited the "quantum"

facility for lab demonstrations. This facility is constantly being shown to leading experts in quantum optics.

Notes

1. S. G. Lukishova and L. J. Bissell, "Nanophotonic advances for room-temperature single-photon sources," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, ed. R. W. Boyd, S. G. Lukishova, and V. N. Zadkov (Cham: Springer, 2019), 103–78.
2. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; S. G. Lukishova, "Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: Teaching quantum mechanics and nano-physics with photon counting instrumentation," *Proceedings of SPIE* 10452, paper 21-1, 14th International Conference on Education and Training in Optics and Photonics (ETOP), May 29–31, 2017, Hangzhou, China.
3. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; Lukishova, "Quantum optics and nano-optics teaching laboratory."
4. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; S. G. Lukishova, N. Bigelow, P. D'Alessandris, "Development of multidisciplinary nanotechnology undergraduate education program at the University of Rochester Integrated Nanosystems Center," paper 10-1, 14th International Conference on ETOP, May 29–31, 2017, Hangzhou, China.
5. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/.