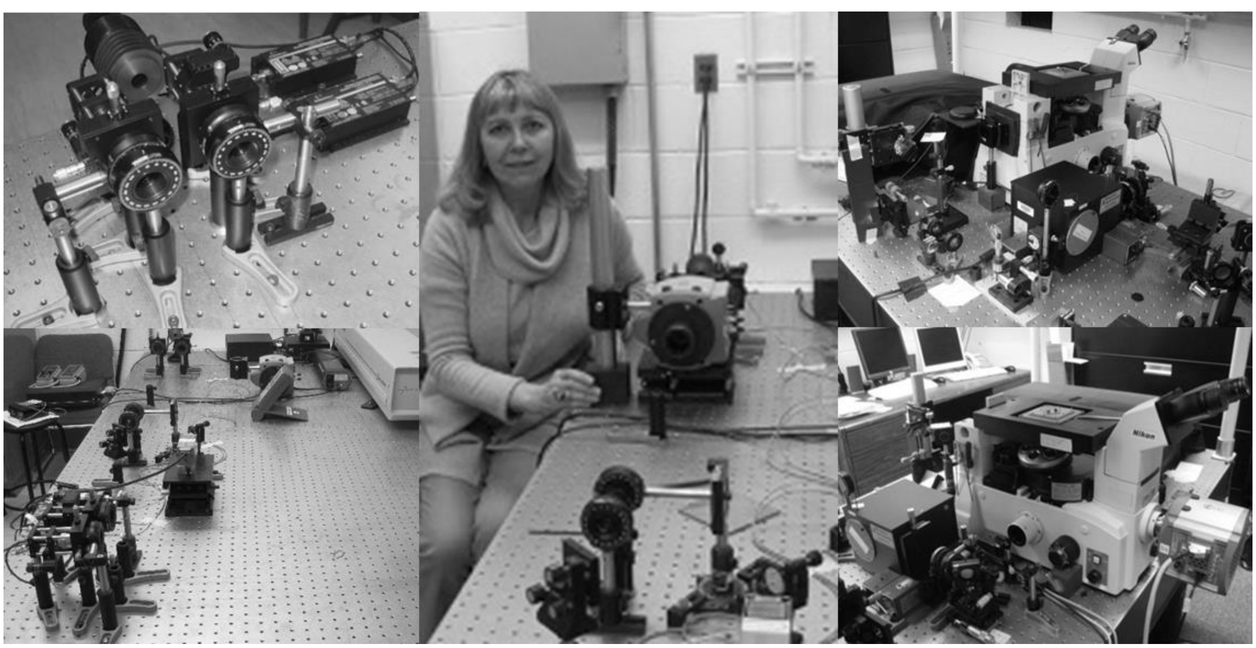
Single and Entangled Photon Sources: Teaching Quantum and Nano-Optics with Modern Photon Counting Instrumentation

Svetlana G. Lukishova

Quantum mechanics is one of the most challenging topics of modern physics in science and engineering education, but it is now being applied to important technological problems. Enormously powerful computers and total communication security are the future goals of quantum information technology on the way to the market. 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 Teaching Laboratory Facility at the Institute of Optics: Some History

The first Quantum Optics and Quantum Information teaching laboratory facility at the Institute of Optics was built more than a dozen years ago. Initial equipment for the entanglement and Bell's inequality teaching experiment was borrowed from Lucas Novotny who also provided references [1, 2]. Graduate student Anand Kumar Jha (now a quantum optics professor in Indian Institute of Technology) assembled a polarization entanglement setup with two type I BBO crystals [3]. Other labs were based on my research facility on single-photon generation and characterization [4] funded by ARO and NSF Material Research Instrumentation grants. In 2006, I started to teach a 4-credit hour course with the same name for both undergraduate and graduate students.



Svetlana Lukishova with her equipment for single and entangled photon sources.

Later donation of a single-frequency argon ion laser from the Spectra Physics division of Newport Corporation, the University of Rochester Kauffman foundation Initiative award, Per Adamson's help and Wayne Knox's support permitted establishing a new entanglement setup at the level of a research unit and in a larger room. A new step was started from support of Carlos Stroud, a director of the Center for Quantum Information, and our two NSF educational grants of 2007─2012. Now Quantum Optics, Quantum Information and Nano-Optics research and educational facility is located in three separate rooms of the Institute of Optics with total 587 sq. ft. My course OPT 253/OPT 453/ PHY 434 Quantum Optics and Nano-Optics Laboratory [5, 6] became popular among the students. Some of the former students of this class grew to become quantum-optics professors of leading universities (Mehul Malik, Zhimin Shi, Omar Magaña-Loaiza, Heedeuk Shin).

Anand Kumar Jha (left), Joe Choi (center), Luke Bissell (right)

Currently this course consists of ten lectures and four 6─15 hours labs [5, 6]: (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; (4) single-photon source II: Hanbury Brown and Twiss setup. Fluorescence antibunching. These labs are in constant development. For instance, my Wadsworth C. Sykes Faculty Engineering Award of the Hajim School of Engineering and Applied Sciences permitted to a very enthusiastic teaching assistant Joe Choi to build a new entanglement setup (the third one for this class) pumped with a high-power blue diode laser. Joe Choi as well as Anand Kumar Jha were very creative, occasionally insisting with energy and passion on including some measurements that were not planned earlier. I also received help on the single-photon source setup from Luke Bissell, my and Carlos Stroud's Ph.D. student. During the early stage of this setup, Lucas Novotny and his group, especially his postdoc Andreas Lieb, were very helpful by providing us with sophisticated LabView-based software for imaging single-emitter fluorescence.

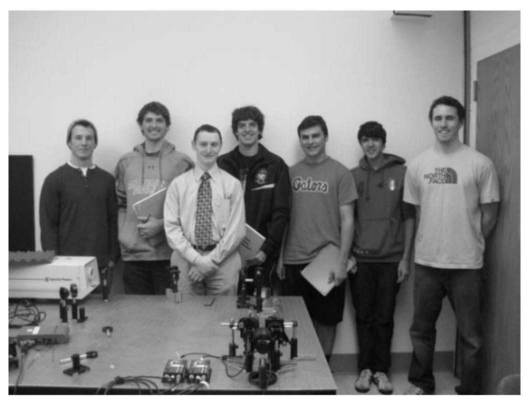
Students of 2016 Fall class OPT 253 on the lab lecture.

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, e.g., single-photon counting avalanche photodiode modules, electron multiplied CCD-cameras, time correlated single-photon counting card, atomic force microscope, etc. In addition to work on my research setup on single photon generation and characterization, in the two labs students are using samples with single emitters in nanostructures that nobody else before them had ever investigated, which, for instance, were prepared at the Cornell NanoScale Science and Technology Facility. Occasionally in the class students obtained results that were reported later at the top professional conferences or included in journal publications, e.g., the first photon antibunching from a single nanocrystal quantum dot within bowtie plasmonic nanoantenna. This intentional blurring of the dividing line between "education" and "research" strongly boosts student interest. Here is one of the students' response after taking OPT 253: *"…working with cutting edge material, doing true research as an undergraduate, learning lab protocol. I believe that my write-ups for future anything will be greatly improved after having gone through this course".*

This teaching facility is constantly being shown to leading experts in quantum optics. Among them were Federico Capasso (Harvard University), Alain Aspect (Institut d'Optique), Peter Knight (Imperial College), Anton Zeilinger (University of Vienna), Prem Kumar (Northwestern University), James Franson (University of Maryland, Baltimore County), Paul Kwiat (University of Illinois at Urbana-Champaign), Kiko Galvez (Colgate University), etc. Participants of the OSA symposium Quantum Optics and Quantum Engineering for Undergraduates that I organized in Rochester in 2008 also visited this facility.

A short, three-hour lab versions of all "quantum" labs were developed for the students with diverse backgrounds. More than 500 students of the University of Rochester carried out different versions of these labs (from 2006 to Fall 2018) with lab reports submission or poster presentation. "Quantum" labs were included to the following classes:

(1) **Freshmen**: It became a tradition, that every year freshmen from OPT 101 class 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 (Luke Bissell, George Gehring and Zhimin Shi).



George Gehring (third from the left) with one of the freshmen "quantum" groups of OPT 101 (2010).

(2) **Juniors and Seniors**: In another class, OPT 223 Quantum Mechanics for Optical Devices taught by Carlos Stroud, three-hour versions of entanglement and single-photon interference labs with submission of graded lab reports were introduced. In my class OPT 204 Sources and Detectors labs and lab lectures a single-photon interference lab was included. One lecture-workshop of this class is devoted to nonclassical light sources, so every junior/senior at the Institute of Optics is familiar with quantum entanglement and photon antibunching.

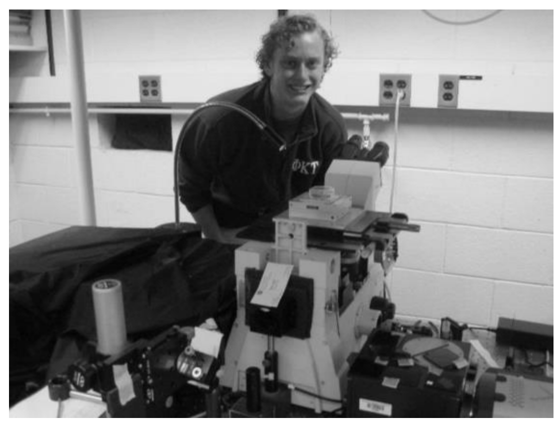
(3) **Department of Physics and Astronomy:** An entanglement lab at the Institute of Optics became popular also among physics students of the advanced laboratory class PHY 243 W.

Program on the Certificate in Nanoscience and Nanoengineering

In 2015, the Quantum Optics, Quantum Information and Nano-Optics research and educational facility became the basis for the undergraduate program towards the Certificate in Nanoscience and Nanoengineering [7, 8], initially suggested by Nick Bigelow, a director of the University of Rochester Integrated Nanosystems Center (URnano). This program was supported by our NSF grant and I am leading it. From 2015 to May 2018, 27 students (mostly from the Institute of Optics) were awarded the Certificate. To accomplish this program students should take two classes in the field of nanoscience or nanotechnology, carry out a one semester research or design project in this field and take a required new class Nanometrology Laboratory OPT 254/PHY 371 (started in Spring 2015). This class consists of three experimental modules: (1) electron microscopy (SEM and TEM), (2) atomic force microscopy, and (3) confocal fluorescence microscopy. Its uniqueness is in students' practical experience in three main expensive nanometrology instruments in one class. Another important feature of OPT 254 is student's constant supervision on these instruments by the experts in the fields (Brian McIntyre, Semion Papernov and myself), without any teaching assistant involved.

Some titles of students' research and design projects for the Certificate are:

- Development of micro-arrayed label-free biosensor using theoretical & experimental analysis of arrayed imaging reflectometry (Miller's lab, Biomedical Engineering).
- Adaptive optics scanning light ophthalmoscope (nanoscale measurements) and how it can effect a disease called Achromatopsia (Merigan's lab, Center for Visual Science).
- The effects of nanoparticle-mediated siRNA delivery on human mesenchymal stem cell proliferation (Benoit's lab, Biomedical Engineering).
- RF Bias-assisted sputtering of Silicon Nitride thin films on Silicon wafers (Cardenas' lab, Optics).
- A polarization sensitive atomically-thin photodiode (Vamivakas' lab, Optics).
- Quantum-enabled super-resolution microscopy (Vamivakas' lab, Optics).
- Single photon sources based on single emitters in plasmonic gold bowtie nanoantennas (Lukishova's lab, Optics).
- Nano-roughness scatterometer (design project, Optics with Sydor Optics)
- Quantum key distribution using time and phase bin single photons with the waveguide (or fiber) structures (design project, Optics with Harris Corporation).



Senior Andrew Kruse is working on his research project on nanodiamonds applications to the single-photon sources. He was awarded the Certificate in 2016.

Here is one Optics student's letter after this student's awarding the Certificate:
"After taking your nano-metrology courses, I have decided to pursue a Ph.D. in photonics & nanoscale optical devices. I loved that I learned, and I want to do it for the rest".

Dissemination of Quantum and Nano-Labs: Teaching Students and Professors from Monroe Community College and other Colleges and Universities

All NSF grants supported teaching Monroe Community College (MCC) students in quantum optics and nano-optics laboratory and 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 labs. On the "quantum" facility, MCC students learned entanglement and Bell's inequalities, single-photon interference, and atomic force microscopy. In UR-nano, they worked in a clean-room environment on photolithography under the supervision of Brian McIntyre.

Paul D'Alessandris (right) from MCC with his students in the single-photon interference lab of the Institute of Optics

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 my "quantum" labs. Later RIT established their own quantum-optics teaching lab. Stephen Preble established an entanglement teaching lab at RIT learning my experience.

In August 2011, I participated in the Immersion Program of the Advanced Laboratory Physics Association (ALPhA) [9] and hosted six visitors from different universities for 3 days [5], familiarizing them with UR lab-course experience on photon quantum mechanics: M. Braunstein (Central Washington University), J. Buchholz (California Baptist University and University of California, Riverside), T. Perera (Illinois Wesleyan University), M.C. Sullivan (Ithaca College), W.F Smith (Haverford College) and D. Dominguez (Texas Technical University).

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 my "quantum" facility. They also prepared 1D-photonics bandgap structures for single-photon source applications from cholesteric liquid crystals. I also shared my experience in quantum optics labs with the University of Oklahoma, Tulsa, upon invitation in 2010. Several students' groups (more than 250 students) from the University of Rochester, Colgate University, and Alfred University visited “quantum” facility for lab demonstration during this decade.

Svetlana G. Lukishova is a group leader and adjunct professor of the Institute of Optics

References

1. D. Dehlinger and M.W. Mitchell, “Entangled photon apparatus for the undergraduate laboratory”, *Am. J. Phys*. 70, 898-902 (2002).
2. D. Dehlinger and M.W. Mitchell, “Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory”, *Am. J. Phys*. 70, 903-910 (2002).
3. P.G. Kwiat, E. Waks, A.G. White, I. Appelbaum, P.H. Eberhard, “Ultrabright source of polarization-entangled photons”, *Phys. Rev*. A. 60, R773-R776 (1999).
4. S.G. Lukishova and L.J. Bissell, “Nanophotonic advances for room-temperature single-photon sources”, in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. Boyd, S. Lukishova, Svetlana, V. Zadkov (Eds.), Springer Series in Optical Sciences, Vol. 217, chapter 4.
5. S.G. Lukishova, S.G., “Quantum Optics, Quantum Information and Nano-Optics Laboratory”, http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/.
6. S.G. Lukishova, “Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: teaching quantum mechanics and nano-physics with photon counting instrumentation”, *Proceed. SPIE*, Vol. 10452, the 14th International Conference on Education and Training in Optics & Photonics (ETOP), May 29-31, 2017, Hangzhou, China paper 21-1.
7. https://www.rochester.edu/urnano/education/certificate_program.html
8. S.G. Lukishova, N. Bigelow, P. D’Alessandris, “Development of multidisciplinary nanotechnology undergraduate education program at the University of Rochester Integrated Nanosystems Center”, Proceed. SPIE, Vol. 10452, the 14th International Conference on Education and Training in Optics & Photonics (ETOP), May 29-31, 2017, Hangzhou, China, paper 10-1.
9. https://advlab.org/immersions.html