How to teach quantum in the age of the second quantum revolution: overview of the current state of the art

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ABSTRACT

Overview of findings and outcomes is presented from several symposia on Quantum Education as well as from most important journal publications in this field including the author's own experience at the Institute of Optics, University of Rochester and 2023 ETOP special symposium supported by the Institute of Optics. Seven topics will be covered, namely: (1) easily understandable and affordable experiments with single and entangled photons; (2) how to teach the formalism of quantum optics in the age of quantum computing and communications and how much mathematics is needed; (3) how to improve students' learning, especially for large enrollment, and how to evaluate what the students learned; (4) curriculum development: how to elicit average students' interest; (5) training quantum optical technicians; (6) K-12 education, outreach activity, and games devoted to "quantum"; (7) engagement of non-STEM majors.

Keywords: quantum labs, students' training, ETOP special symposium, improvement of students' learning

1. INTRODUCTION

The symposium "How to teach quantum in the age of the second quantum revolution" was held in May 2023 during the 17th Conference on Education and Training in Optics and Photonics (ETOP) with support of the Institute of Optics, University of Rochester, USA [1-3]. This is not the first such forum on education in Quantum Information Science and Engineering (QISE). For instance, two earlier meetings resulted in QISE educational roadmaps in journal papers [4, 5]: the November 2019 Kavli Futures Symposium, "Achieving a Quantum Smart Workforce" [6], and the February 2021 National Science Foundation (NSF) Workshop on Quantum Engineering Education [7]. The NSF conference "Key Concepts of Quantum Information Science (QIS) Learners" [8] identified a set of nine key concepts for QIS learners [9]: *quantum information science*; *a quantum state*; quantum applications are designed to carefully manipulate fragile quantum systems without observation to increase the probability that the final *measurement* will provide the intended result; *the quantum bit, or qubit*; *entanglement*; for quantum information applications to be successfully completed, fragile quantum states must be preserved, or kept *coherent*; *quantum computers*; *quantum communication*; *quantum sensing*.

The special, open access, issue of SPIE Optical Engineering with ten papers was devoted to QISE education [10]; Physical Review Physics Education Research, American Journal of Physics and other journals regularly publish QISE education devoted papers.

2. OVERVIEW OF ETOP 2023 QUANTUM SYMPOSIUM

The program committee of 2023 ETOP Quantum symposium [M.T. Posner (Optonique, Canada), B.E.A. Saleh (University of Central Florida, USA), F. Setzpfandt (Friedrich Schiller University, Germany), and the author of this paper] focused on the *optics* aspects of QISE. Among 17 talks and 3 posters from the USA, Australia, Colombia, Germany, Mexico, Spain, and the United Kingdom, the main discussed questions were focused on the speakers' experience in teaching students the photonic aspects of quantum mechanics including labs, lectures, curriculum development and tools.

Seven topics were covered, namely: (1) easily understandable and affordable experiments with single and entangled photons; (2) how to teach the formalism of quantum optics in the age of quantum computing and communications and how much mathematics is needed; (3) how to improve students' learning, especially for large enrollment, and how to evaluate what the students learned; (4) curriculum development: how to elicit average students' interest; (5) training quantum optical technicians; (6) K-12 education, outreach activity, and games devoted to "quantum"; (7) engagement of non-STEM majors.

Optics Education and Outreach VIII, edited by G. Groot Gregory, Anne-Sophie Poulin-Girard, Proc. of SPIE Vol. 13128, 1312807 · © 2024 SPIE
0277-786X · doi: 10.1117/12.3027899

The following are highlights of the symposium talks and findings on these seven main topics:

1. Teaching experiments for quantum photonics

Almost half of the talks of the symposium were devoted to teaching *experiments*. The symposium was opened by K. Galvez' (Colgate University, USA) invited talk on his almost 20 years' experience with photonic quantum mechanics experiments [11] with detailed description of basic apparatuses and their cost including motorizing labs and remote options for entanglement and Bell's inequalities, single-photon interference with quantum eraser labs and Hong-Ou-Mandel interferometer.

S.L. Lukishova (University of Rochester, USA) described more than 15 years' experience of the Institute of Optics on the design of an advanced laboratory on quantum and nano-optics, both for undergraduate and graduate students [12]. She outlined four experiments on the generation and characterization of entangled and single (antibunched) photons that can be performed in one lab period. From 2006 to spring 2024, more than 900 students have utilized 3-hour labs (including 144 students from a local community college). In addition, sturdy, universally accessible, quantum "mini labs" that can be routinely conducted in high-attendance classes, during 1.5 to 3 hours of a lab time were introduced in several optics' classes. During the pandemic, remote lab operations and teaching through zoom were developed [13].

Four contributions from the Friedrich Schiller University Jena, Germany, highlighted teaching experiments. R. Sollapur, in his first talk, outlined a master's-level course Experimental Quantum Technologies that contained lectures and 8 hands-on modules (both home-built and commercial) on quantum computing, single-photon interference, Hong-Ou-Mandel interferometer, entanglement, and quantum tomography, sensing via NV-centers in diamonds, etc. In his second talk, R. Sollapur described an experimental, elective online course for master's students, with a certificate issued after course completion. P. Scheiger discussed entanglement and hidden parameters explored with real and analog experiments. S. Aehle described the polarization analogy module and corresponding teaching concepts that present analogies to quantum phenomena.

J. Álvarez (Universidad de los Andes, Colombia, and University of Oxford, UK) spoke about measuring Wigner functions of quantum states of light in the undergraduate laboratory. This experiment was tested with 25 students that took the quantum optics course at the Universidad de los Andes in Bogotá, Colombia. The activity was designed to provide a similar experience with virtual experimental sessions with an open-access, user-friendly interface that includes detailed instructions and sample data.

E. Deveney (Bridgewater State University, USA) described his experience with commercial entanglement demonstrator module quED and recommendations from the book of M. Beck [14] to teach quantum mechanics in a quicker, more intuitive, and accessible way.

2. Formalism of quantum optics

The idea of explaining quantum physics by avoiding mechanics and starting with the optical concepts of polarization and entanglement of photons was the basis of an invited talk by A. Lvovsky (University of Oxford), who outlined chapters of his book [15], the structures of his classes and laboratory components on polarization, entanglement, and IBM quantum computing.

In another talk entitled "Should we trade off higher-level math for abstraction to improve student understanding of quantum mechanics?" on the example of the harmonic oscillator, J. Freericks (Georgetown University, USA) showed how using abstraction lightens the mathematical prerequisites.

3. Studies of quantum workforce landscape and undergraduate quantum optics teaching labs

H. Lewandowski's invited talk (University of Colorado Boulder, USA) was based on interviews with 21 people in the quantum industry and surveys of 56 companies in the Quantum Economic Development Consortium (QED-C) about preparation of students and postdocs to work in the quantum industry and the skills and knowledge that are currently required. Her group's findings showed a high need for hands-on experience. There was also evidence of the apparition of regional needs based on existing clusters of excellence, which echoes findings from studies in Canada of the need for quantum skills for the photonics industry [16]. Undergraduate experimental quantum education in different universities in the USA was studied by surveys with 28 instructors teaching quantum optics experiments, 14 in-depth interviews with some of them, and 14 interviews with their students. One of the most important goals of both instructors and students selected is "seeing quantum mechanics in real life". Some results of this talk were published in Refs. [17-19].

4. Curriculum development: QISE degree programs at different levels

At the University of Rochester (S. Lukishova), in addition to quantum laboratory classes, various aspects of QISE were included in an undergraduate program named "Certificate in Nanoscience and Nanoengineering" completed by 49 students (May 2024) since 2015 [13].

R. Raghunathan (Virginia Tech, USA) discussed the role of a commercial quantum key distribution test bed as the quintessential tool offering "hands on" training and skills to Master of Engineering degree students. Of particular importance was the emphasis on the participation of experts from industry, especially companies looking to incorporate quantum technologies into their product/service portfolios, as well as companies developing such technologies. Robust quantum education curricula and experiential learning approaches are evolving on a wider scale, by partnering with institutions such as Historically Black Colleges and Universities, both locally within the state of Virginia, as well as nationwide.

T. Searles (University of Illinois at Chicago, USA) presented the state of the art of quantum engineering degree programs in the USA and globally. Specifically, he described the work on updating an ABET-accredited Engineering Physics curriculum at his university enticing students to gain experience and knowledge in quantum engineering.

5. Quantum technicians

M. Hasanovic (Indian River State College, USA) shared his experience and results of EdQuantum, an NSF-funded project with the goal of developing a curriculum for the training of future quantum technicians [20] (invited talk). The intent of the proposed curriculum is to provide an important first step in quantum education for an associate degree audience. The curriculum relies heavily on the visual hands-on approach based on the commercially available quantum educational hardware. Through algebra-based theory and simple experiments, the curriculum strives to bring complex quantum science to the level understandable by individuals without a strong scientific background.

6. K-12 education

D.M. Silberman (Optics Institute of Southern California, USA) outlined the best practices he has found among high-school programs and merged them with his own experience in optics and photonics education outreach endeavors. He offers a concise path for quantum outreach volunteers such as Optica and SPIE Student Chapter members at colleges and universities and professionals in industry (easy-to-follow, written materials and easy-to-acquire hands-on materials for low-cost laboratory experience).

A. Venegas-Gomez (Qureca Ltd, UK) presented the "Qureka! Box", a specialized educational tool demonstrating the core concepts of quantum computing. The "Qureka! Box" includes 3D representations to support understanding and visualization of basic quantum concepts, student worksheets, and instruction guides for students and teachers through active, hands-on, and game-based learning resources. These include visualization tools such as a 3D Bloch sphere and the "QbitBox" to familiarize students with the concept of superposition, entanglement, interference and measurement, and a card game that demonstrates the difference between classical and quantum computers.

7. Engagement of non-STEM majors

R. Manfield (University of Queensland, Australia) spoke about innovative curricula on harnessing quantum technologies for commercial purposes that guide both industry and government players in making promising use of their resources. A key question arises as to how to best educate a distributed skilled workforce to deliver and capture value from quantum innovations. This learning challenge suggests a massive open online course (MOOC) [21] to align quantum science with quantum strategy.

The main outcome of the 2023 ETOP symposium "How to Teach Quantum in the Age of the Second Quantum Revolution" is publication in symposium proceedings eleven papers on the SPIE [2] and Optica [3] websites.

ACKNOWLEDGEMENTS

The author thanks the members of the symposium program committee M.T. Posner, B.E.A. Saleh, F. Setzpfandt, and a co-chair of ETOP M. McKee for helping in organizing this symposium. The symposium was supported by the Institute of Optics, University of Rochester.

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